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STANDING IN CHILDREN WITH BILATERAL SPASTIC CEREBRAL PALSY: ASPECTS OF MUSCLE STRENGTH, VISION AND MOTOR FUNCTION

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Standing in children with bilateral spastic cerebral palsy: Aspects of muscle strength, vision and motor function
THESIS FOR DOCTORAL DEGREE (Ph.D.)

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To the children and adolescents who contributed to this book

ABSTRACT

The movement and posture disorder of cerebral palsy (CP) is presumed to mainly be a consequence of the motor disorder, but accompanying disturbances with sensations and perception have also been suggested to influence motor function. The aim was to investigate factors influencing standing posture in children with bilateral spastic CP (BSCP) with varying standing abilities.

Three-dimensional motion analysis with surface electromyography was recorded to describe posture during three standing tasks: in a habitual standing position, while blindfolded, and during an attention-demanding task. Muscle strength in the lower limbs was measured with a hand-held dynamometer. Motor function was measured with the Gross Motor Function Measure. The children also underwent a neuro-ophthalmological examination.

Almost half of the participants required hand-held support to stand. Investigation of standing posture verified a crouched body position during standing which was more obvious in the children who required hand-held support. Muscle strength measurements indicated that the children in both groups were equally strong in the lower limb muscles despite their variation in standing abilities. The children who stood with support were as capable to perform motor activities in lying, sitting and kneeling positions as the children who stood unsupported.

Vision influenced posture differently depending on the children's standing ability. During the attention demanding task, the children who stood unsupported stood more still and with less lower limb muscle activity. While blindfolded, they adapted their posture to the environmental change by activating muscles around the ankle with no changes in overall body position. In contrast, the children who required hand-held support to stand used another strategy; the already flexed body position became even more flexed, and muscle activity increased in the knee extensors while blindfolded, despite the use of external support.

Motor disorders could not explain the support for standing or the crouched body position during standing. The children were equally strong in the lower limb muscles and had reasonably similar abilities to perform motor activities in positions with no requirement of standing on the feet opposing gravity. The crouched body position and the reduced ability to maintain posture while blindfolded indicate proprioception deficits in the children who required support. The increased quadriceps muscle activity could be an indication of compensatory co-contraction caused by perceptual impairments. That motor function difficulty arises in a standing position opposing gravity indicates that standing difficulties may be attributable to sensory and/or perceptual disturbances.

LIST OF SCIENTIFIC PAPERS

This thesis is based on the following original articles and manuscripts, which in text have been referred to by their Roman numerals:

I. Lidbeck CM, Gutierrez-Farewik EM, Brostrom E, Bartonek A. Postural orientation during standing in children with bilateral cerebral palsy. Pediatr Phys Ther. 2014;26(2):223-9.

II. Lidbeck C, Tedroff K, Bartonek A: Muscle strength does not explain standing ability in children with bilateral spastic cerebral palsy: a cross sectional descriptive study. BMC neurology 2015, 15(1):188.

III. Lidbeck C, Bartonek Å, Yadav P, Tedroff K, Åstrand P, Hellgren K, Gutierrez-Farewik EM. The role of visual stimuli on standing posture in children with bilateral cerebral palsy. Accepted in BMC neurology, August 2016.

IV. Lidbeck C, Bartonek Å. Gross motor function and standing ability in children with bilateral spastic cerebral palsy. Manuscript.

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LIST OF ABBREVIATIONS

BSCP	Bilateral Spastic Cerebral Palsy
CP	Cerebral Palsy
sEMG	surface Electromyography
HHD	Hand-held dynamometer
GMFCS	Gross Motor Function Classification System
GMFM	Gross Motor Function Measure
ICF	International Classification of Functioning, Disability and Health
ROM	Range of Motion
SMC	Selective Motor Control
SwS	Standing with Support
SwoS	Standing without Support
TD	Typically Developing
3D	Three-Dimensional
TUG test	Timed Up and Go test

1 INTRODUCTION

The heterogeneous condition of cerebral palsy (CP) is caused by an injury to the immature brain affecting movement and posture development. The attainment of standing and walking can be difficult and an assistive device to accomplish the tasks may be required for some children with CP. In this thesis the emphasis was on the role of possible sensory and perceptual disturbances for standing difficulties in children with CP, based on the concept of an interaction between action, perception and cognition [1]. Aspects of muscle strength, vision and motor function on standing posture were investigated on the level of body functions and structures, and on activity and participation according to the International Classification of Functioning, Disability and Health (ICF) [2]. For simplicity, both children and adolescents were referred to as children.

1.1 CEREBRAL PALSY

1.1.1 Definition

Disorders of the development of movement and posture are the core features of CP. Previous definitions have focused on the motor impairment and its variability (Bax 1964, Mutch et al 1992). Expanded knowledge about the impact of non-motor aspects and neurodevelopmental problems encountered in CP led to an expanded and more comprehensive definition that includes among others, disturbances of sensation and perception in the concept of CP. The nowadays widely established definition of CP by Rosenbaum et al. was published in 2007 [3]:

"Cerebral palsy (CP) describes a group of permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain. The motor disorders of cerebral palsy are often accompanied by disturbances of sensation, perception, cognition, communication, and behaviour, by epilepsy, and by secondary musculoskeletal problems."

The movement and posture disorder of CP is a non-progressive condition which is based on natural history and specific characteristics that persists throughout a lifespan [3]. In the definition the various terms and concepts are clarified. "A group" refers to the heterogeneity of the condition both in terms of etiology and severity of the impairments. "Disorders" refers to disruptions of orderly child development. Moreover, "movement and posture" refer to abnormal gross and fine motor functioning and organization, reflecting abnormal motor control. For the term "activity limitation," the concept of activity from the ICF is used, meaning the execution of a task. The accompanying disturbances of "sensation" refer to vision and other sensory modalities. "Perception" refers to the capacity to incorporate and interpret sensory and/or cognitive information.

1.1.2 Prevalence and etiology

With a prevalence at 2-3/1000 live births, CP is the most common childhood motor disability in developed countries [4; 5; 6]. That means that about 250 children develop some form of CP in Sweden annually. The prevalence of CP has remained stable over time since the 1980s, even though a trend pointing to a decrease in the overall prevalence was recently reported [7]. The development of CP has been related to low birth-weight and prematurity, with a higher prevalence among children born preterm [5; 6]. However, most children with CP are born at term [6].

CP is caused by an injury in the developing child's brain somewhere during pregnancy or up until two years of age [3]. The etiology of the lesion varies, with a multifactorial concept including malformations, inflammations or cerebral circulatory disorders as likely causes [8; 9; 10]. More recently, genetic risk factors have also been reported [11].

1.1.3 Classification

The classification of CP includes four major components: the motor abnormalities, accompanying impairments, anatomic and radiological findings, and causation and timing according to the definition by Rosenbaum et al.[3].

Thus, the predominant motor abnormality should be diagnosed as being spastic, dyskinetic, or ataxic. Thereafter, the spastic type is recommended to be specified by the anatomical distribution as either unilateral or bilateral [12]. The extent to which the individual is limited in their motor function ranges from being mild and barely noticeable to being severely limiting. The functional consequences of the motor abnormalities for the child should preferably be classified by using objective systems. For ambulation, children's self-initiated movement, with an emphasis on sitting, transfer and mobility, the five levels of the Gross Motor Function Classification System (GMFCS) are widely employed [13; 14]. In the age span from 6-12 years, children functioning at level I walk without limitations in all environments. They even perform running and jumping, but speed, balance and coordination are limited; meanwhile, children at level V are transported in a manual wheelchair (Table I). The children's ability to use their hands in daily life activities is commonly classified with the five levels of the Manual Ability Classification System [15]. Children functioning at level I handle objects easily and successfully, at most with limited speed and accuracy, whereas children at level V do not handle objects and have severely limited ability to perform even simple actions. In the heterogeneous condition of CP the motor problems can lead to difficulties with swallowing and feeding, communication, as well as coordinating eye movements. There is a similar scale for classifying communication, and the process of developing a system to classify vision is ongoing [16]. The accompanying disturbances in, for example, vision, sensations, perception and attention are recommended to be classified as either being present or absent, and the extent to which the disorders interfere with the child's activities in daily life should be described. There is continuous work on the development of classification systems based on the current understanding of the condition and its applicability of function in daily life [17].

Table I. The Gross Motor Function Classification System (GMFCS), general headings for each level

GMFCS	
Level I	Walks without limitations
Level II	Walks with limitations
Level III	Walks using a hand-held mobility device
Level IV	Self-mobility with limitations; may use powered mobility
Level V	Transported in a manual wheelchair

Only when the component of cause is evident should causation and timing of the insult be noted. In many children with CP no identifiable cause of the injury can be found even though multiple risk factors may be present. It is recommended that all children with CP are examined with neuroimaging, preferably magnetic resonance tomography.

1.1.3.1 Distribution of CP types

Spasticity is by far the most common dominating neurological symptom, occurring in about 80% of children diagnosed with CP. Among the children with CP, almost 45% have a diagnosis of unilateral CP, and around 35% have a bilateral diagnosis. Approximately 15% of the children have dyskinetic CP, while 5% have ataxia [6]. About half of the children with CP have one or more additional disabilities such as impairment of cognitive capacity, seizure disorders, or visual impairments [18].

1.2 MOVEMENT AND POSTURE

Movements are functions associated with control over and coordination of voluntary movements [2]. Based on the theories about motor control by Shumway-Cook et al., movement arises from an interaction between the individual, the task and the environment [19]. Thereby, the ability to perform motor tasks such as sitting, standing or walking, is determined by the individual child's capacity to meet environmental demands. Within each individual, complex dynamic processes including interaction of perception, cognition, and action are necessary to produce movements. Motor control is defined as the ability to regulate or direct the mechanisms essential to movement [1].

Posture and balance as well as motor control are dynamic functions requiring a continuous interaction between the individual, the task, and the environment [20]. Posture includes different aspects of motor coordination such as maintaining the body position with respect to the environment, controlling the center of body mass with respect to gravity, and stabilizing the body during voluntary movement [21].

The ability to orient the body position in space is based on an interaction between three major sensory systems: the visual, the somatosensory and the vestibular systems [1; 21; 22]. The visual system gives information from the close environment and is primarily involved in planning one's locomotion [23].

The somatosensory systems consist of a multitude of receptors which, through proprioceptive and cutaneous information in combination, sense the position of the body segments in relation

to each other, in contact with the environment and in relation to gravity [22]. The different sensory receptors each respond differently to the somatosensory sensory stimulation. Proprioception is a sensory function of sensing the relative position of body parts according to ICF [2]. Proprioception gives information about the relative position of the body segments in space – egocentric information – and is necessary for the control of movements [24]. The mechanoreceptors in the muscles and tendons provide information about mechanical forces arising within the body itself. Proprioceptors in the muscles and tendons are specialized to detect change in muscle length and muscle tension [25]. Cutaneous receptors give information derived from external stimuli such as hand-held support or active touching – exocentric information.

Vestibular functions are sensory functions that are related to position, balance and movement[2]. The vestibular system has important sensory functions, contributing to perception of self-motion, head position, and spatial orientation relative to gravity [22]. For motor activities, its function is especially important for stabilization of gaze, head orientation and posture [22].

Orientation to space comes from mental functions that produce awareness of one's body in relationship to the immediate physical space [2]. To organize perception and action, there are frames of reference that the body posture can be oriented to, depending on the task and its goal. The frames of reference can be visual, based on external cues in the close environment, or somatosensory, based on information from contact with external objects. In addition, the vestibular system detects gravity, the natural reference enabling perception of the vertical [21; 24; 26]. The brain constructs a spatially corrected framework to detect gravity with processed sensory information from the visual, somatosensory and vestibular systems [24].

Perception is specific mental functions of recognizing and interpreting sensory stimuli including tactile and visuospatial perception according to ICF [2]. Movement is considered tightly related to perception and action [19; 24]. From theories by Berthoz, perception is more than interpretation of sensory information, it is an internal simulation of action [27]. By analyzing information from the surrounding space, from the body position and from produced and received movements, perception is an internal simulation of action required for judging and anticipating movement [22].

Attention is a specific mental functions of focusing on an external stimulus or internal experience for the required period of time, according to ICF [2]. Attentional strategies determine the degree of attention given to a postural task when performing other tasks simultaneously [28].

Regulatory mechanisms of postural control result from an interaction between visual, vestibular and somatosensory information, and the motor activity. In the case of unexpected perturbations, such as after a slip or trip, reactive responses in the hip, knee or ankle are used as a feedback strategy to control the body position in space in relation to the environment. To predict forthcoming movements as well as during voluntary movements, a feedforward strategy with anticipatory postural adjustments is used to stabilize body position in relation to the environment or the task [20; 21]. Berthoz (2000) considered anticipation an internal simulation of movement that through a combination of proprioceptive, cutaneous, vestibular and visual receptors is attributed the sense of movement or kinesthesia (Figure 1) [22].

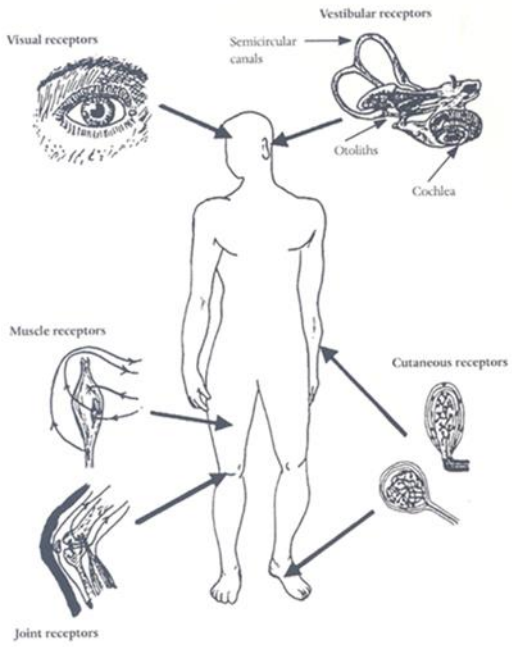

Figure 1. Sensory receptors contributing to the sense of movement (Berthoz 2000). The illustration is reprinted in accordance with the Copyright Guidelines, Harvard University Press.

1.3 STANDING

The basic function of maintaining a standing position opposing gravity is derived from a complex interaction between both sensory and motor systems [20]. For the motor task of standing without support, posture and balance – postural control – are central. Postural control involves controlling the body position in space for *stability* and *orientation* [20; 21].

- Postural stability is the ability to control the center of mass in relation to the base of support
- Postural orientation is the *active alignment* of body segments with respect to each other and the *maintenance* of body position for a task with respect to the environment or with respect to gravity, and is a prerequisite for the ability to maintain a standing position

1.3.1 Standing in cerebral palsy

Typically, posture during standing has been investigated in children with mild CP and in terms of postural stability, including coordination of movement strategies following environmental changes during standing. Previous studies have shown that children with CP tend to have poorer balance, in terms of increased postural sway, during standing compared to typically developing (TD) children [29; 30; 31; 32]. In studies investigating reactive postural control in response to perturbations, children with CP showed less complex movement strategies. They activated all joints simultaneously with altered patterns, tolerated slower speed before stepping, and required more time to recover from perturbations compared to TD children [33; 34]. Moreover, the ability to foresee and adapt posture to predict movements is disturbed and less effective in both standing and in sitting in children with CP compared to TD children [35; 36; 37; 38].

Several studies have reported that children with mild CP and TD children appear to be equally dependent on vision for stability during standing; with occluded vision, postural sway increased to an equal extent in both groups [29; 30; 31]. However, in the studies mentioned, some children with CP reacted to the occluded vision with more apparent instability than others, and the finding was related to sensory disturbances. Instability during standing was related to sensory disturbances in a study by Cherng et al. (1999), and with proprioceptive deficits in a study by Damiano et al. (2013) [29; 39].

1.4 DISTURBANCES IN MOVEMENT AND POSTURE IN CEREBRAL PALSY

The main features of CP are disorders of movement and posture, reflecting motor control deficits with abnormal gross and fine motor functioning and organization [3]. In children with the movement and posture disorders of cerebral palsy, the activity limitations are presumed to be a consequence of the motor disorders, however, the disorder is often accompanied by disturbances of sensation, perception, and cognition [3].

The motor impairments appear early in a child's life and can often be recognized before the age of 18 months, through observations of consistently abnormal postures and difficulties reaching motor milestones such as sitting, standing and walking [3; 40]. The children's ability to fulfill static and dynamic motor activities, from lying down to finally walking and running, is frequently assessed with the Gross Motor Function Measure (GMFM) [41]. The instrument is a valid and reliable measure of a child's motor capacity in a testing situation [42; 43]. All items included in the measure are expected to be accomplished by a typically developing five-year-old child [41]. The items in the test that measure a sit-to-stand activity have been reported to be predictable for independent walking in young children with CP [44].

Motor growth curves based on assessments with the GMFM related to age and gross motor classification, according to GMFCS levels, were developed and published in 2002 [45]. The curves can be used to evaluate and, to some extent predict motor development in children with CP [45]. Within the curves, the commonly described heterogeneity of motor function both between and within the GMFCS levels, becomes visible. In some children with CP there is a discrepancy between motor capacity during a testing session and functional use in daily life activities that is not fully understood. Studies investigating mobility methods in various environments reported that children with CP used mobility methods requiring the most motor control such as walking at home in settings where obstacles were predictable, compared to at school, which is a more unpredictable environment, using a wheel chair [46; 47].

1.4.1.1 Motor disorders

In children with the heterogeneous diagnosis of CP, a combination of motor disorders may occur simultaneously. Spasticity, muscle weakness and, difficulties performing voluntary movements are characteristic disorders that occur, more or less evidently, in most CP diagnoses. These disorders can be quantified by using valid and reliable instruments in children with CP. Consequently, motor disorders have been the focus in studies investigating motor function.

Spasticity can be defined as "*A motor disorder characterized by a velocity-dependent increase in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from hyperexcitability of the stretch reflex, as one component of the upper motor neuron syndrome"* [48]. The Ashworth scale can be used to assess spasticity as a velocity-dependent increased resistance to passive stretch at rest in a clinical setting [49]. In general, there is little or no spasticity present in the lower limbs during the first year of life in children who develop spastic CP. In a study investigating the development of spasticity in children with CP, it was reported that muscle tone increased from the age of one year up to four years, followed by a continuous decrease up to twelve years of age [50]. Spasticity has been found to be marginally related to motor function in a study by Ross et al. (2007) [51], and to motor function development by Gorter et al. (2007) [52].

Muscle weakness has been considered a secondary impairment in CP, though highly associated with the movement disorder [53; 54]. Muscle weakness can be defined as the inability to generate normal voluntary force in a muscle or normal voluntary torque about a joint without differentiating the cause of the difficulty [55]. Muscle strength, as the ability to produce force at a specific position-dependent muscle length, can be measured with a hand-held dynamometer (HHD) [56]. In several studies muscle weakness has been related to the development of motor activities such as walking independently in children with CP [56; 57; 58]. In a recently published study, functional strength or dynamic postural control, measured as the ability to attain sitting and standing from a chair, was found to predict walking ability in 75% of the 80 children who were tested [44]. The awareness of muscle weakness and its associations with difficulties in achieving motor activities have led to resistance training becoming a commonly recommended intervention for children with CP. Through exercise, muscle strength undoubtedly improves, but functional benefits for the children have been difficult to demonstrate [59; 60; 61; 62].

Selective motor control (SMC) enables independent control of joint motion [55]. Thus, reduced SMC leads to impaired ability to isolate the activation of muscles in a selected pattern in response to demands of a voluntary posture or movement [55]. Impaired SMC in the lower limbs has been found to interfere with motor function and be related to motor capacity measured with the GMFM in children with CP [63; 64].

Muscle co-contraction or co-activation is a mechanisms that regulates simultaneous activity of agonist and antagonist muscles crossing the same joint. Co-activation is considered a task-related strategy that can aid stability and/or precision, but not always efficiency, of a movement during the learning of new skills and during the performance of functional activities that are related to uncertainty or complexity in execution [65; 66]. In children with CP, abnormal levels of antagonist activation have been reported to coincide with both voluntary muscle activation and with motor activities such as sitting and standing. In studies investigating muscle activity during maximal voluntary contraction, higher levels of co-activity in both the antagonist and agonist muscles were found in children with CP compared to TD children [67; 68].

Secondary musculoskeletal problems such as musculotendon contractures and bony torsion deformities in children with CP are common [3]. A decrease in lower limb joint range of motion (ROM) in the hip, knee and ankle from the age of two years was reported in a population-based

study from Sweden [69]. Factors such as physical growth, weakness and spasticity, have been suggested to influence the development of contractures in CP [3]. Moreover, posture and disuse are reported contribute to muscle stiffness and the development of contractures in CP [40; 70; 71]. The influence of decreased ROM on motor function is not clear [72]. In one study passive joint ROM in the lower limbs was reported to be predictive of standing balance, as amount of sway, in children with CP who stood without support [73]. In a recently published paper, reduced ROM was weakly associated with motor function development in children with CP [64].

1.4.1.2 Visual impairments

Visual impairments are common in children with CP [3; 74; 75; 76]. Often, visual dysfunction is an invisible impairment that may limit children in their motor ability and orientation, and cause difficulties in guiding movements [23; 74; 76]. As such, delayed motor development and tripping and falling may be over-attributed to poor motor function in children with visual impairments [40].

1.4.1.3 Proprioceptive deficits

Proprioceptive deficits including disturbances with both position sense and sense of limb movement in the lower limbs have been recognized in children with CP [77; 78]. Moreover, proprioceptive deficits have been related to instability during standing and to reduced walking speed in children with CP who could stand unsupported [29].

1.4.1.4 Perceptual disturbances

Perceptual disturbances with difficulties incorporating and interpreting sensory information may occur among children with CP [3]. From this, there are theories that impairment in the perceptive system may lead to failure with complex neurological processes such as organizing sensory information from the body and environment in order to plan, control, guide and produce controlled motor behavior [23]. Spatial disorganization, such as in difficulty identifying a target on the wall after being passively turned, has been reported, but only in children with unilateral CP [79].

1.4.1.5 Attention

In children with CP, cognitive processes of attention also may be disturbed [3]. To our knowledge, the influence of attention on motor function has sparsely been studied in children with CP. There is some evidence that when attention is shifted away, external to the body, stability during standing improves in children with unilateral spastic CP who stand independently [31; 80].

1.4.2 Disturbances in bilateral spastic cerebral palsy

Bilateral spastic CP (BSCP) is the most heterogeneous of all CP diagnoses, including children functioning at all five GMFCS levels. Among children with BSCP, around 40% of the children are classified at GMFCS level I, 20% at each of levels II and III, 15% are at level IV, and only 5% of the children at level V [4]. In this thesis, the focus is on children with BSCP, GMFCS levels I to IV, which covers around 30% of the entire population with CP [4; 6]. Some

characteristic features of motor, sensory and perceptual origin, and their influence on motor function among children with BSCP are addressed below.

Spasticity, the predominant motor abnormality in children with BSCP, was for long considered an impairment determinant in the acquisition of motor abilities in children with BSCP. As such, spasticity and its relation to motor function has been extensively investigated and has been a target for interventions. In one study spasticity was found to account for only a small variance between the ability to walk with or without assistive devices in children with BSCP [51]. Moreover, there is limited evidence that medical interventions for spasticity reduction lead to functional benefits for children with CP [81; 82; 83; 84; 85]. It is important to note is that reduced spasticity may be a goal that has great value for children regarding factors other than motor function, such as reduced pain and/or improved well-being [86].

Children with BSCP are substantially weaker in the lower limb muscle groups, most prominently around the ankle and in the hip muscles compared to TD children [57; 58; 87]. Children who are independent walkers in all environments functioning at GMFCS level I are stronger in most lower limb muscles compared to children with more limited walking ability at GMFCS levels II and III [58; 87; 88]. Consequently, muscle strength has been considered important for motor function development and walking ability either with or without an assistive device in children with BSCP [51; 58; 89].

In studies investigating postural adjustments following perturbations during both sitting and standing, co-activation in the antagonistic muscles has been found in children with BSCP [90; 91; 92]. In the study by Brogren et al. (2001), the muscle responses were almost intact when children were tested in a stable crouched sitting position compared to a more erect cross-legged sitting position [91]. The authors concluded that the commonly observed crouched sitting position in children with CP might be a solution to the experience of encountering instability caused by a sensory-motor problem. Other authors have related experience of stiffening of one or more body parts during unexpected perturbations as a response to not tolerating sudden movements [93]. The stiffening was interpreted as a sign of perceptual impairment, and was designated as postural freezing by the authors.

Proprioceptive disturbances have been related to instability in standing and walking speed in children with BSCP who stood independently [29]. Moreover disturbed sensory information from the lower limbs was suggested as contributing to walking difficulties in children with BSCP requiring assistive device for walking, in a recently published study [94].

Perceptual impairments with difficulties organizing sensory information from the body and the environment have been related to motor difficulties expressed as uneasiness and fear of being upright without a narrow surrounding environment, hand support or personal support in children with BSCP [95]. In a recently published study, clinical signs such as startle reaction, eye blinking and posture freezing were identified as sensitive for revealing perceptual disorders in children with BSCP [93]. Moreover, Ferrari et al. (2010) reported that difficulties accomplishing a reaching task in sitting were related to perceptual disturbances in children with BSCP [38]. In addition, difficulties extending the legs and producing antigravity reactions during standing have been related to difficulties in detecting gravity, the natural frame of reference in children with BSCP [95].

1.5 RATIONALE

Children with CP usually have walking and standing difficulties, with some requiring support for standing. The movement and posture disorder of CP is presumed to mainly be a consequence of the motor disorder but it has been suggested that they are also attributable to accompanying factors such as disturbances of sensation and perception. This thesis is an attempt to investigate standing from a perspective that takes the influence of sensory processes into account.

2 AIMS OF THE THESIS

The general aim of this thesis was to investigate factors influencing standing in children with bilateral spastic CP (BSCP), GMFCS levels I-IV, with respect to their varying standing abilities with or without the requirement of hand-held support.

The specific aims of the studies were to:

- Investigate postural orientation, that is segment alignment and maintenance of joint position, during quiet standing
- Explore strength in the lower limbs muscles
- Explore the influence of visual stimuli on standing posture while blindfolded and during an attention demanding task
- Explore motor function in other positions than standing, such as lying, sitting, and kneeling

3 METHODS

3.1 STUDY DESIGN

Studies I-IV were prospective cross-sectional descriptive studies.

3.2 STUDY OUTLINES

Study I
Three-dimensional (3D) motion analysis was conducted to investigate postural orientation with segment alignment – body position – and maintenance of joint position – body movements – during standing in children with CP. Twenty-six children with BSCP, GMFCS levels I to IV, and 19 TD children participated in Study I. Data was analyzed with respect to standing ability with or without support in the children with CP. Data from the TD children were used as reference values.

Study II
Muscle strength was measured with an HHD and 3D motion analysis was conducted to explore lower limb muscle strength and whether the ability to produce strength was influenced by different seated conditions in children with BSCP. Twenty-five children with BSCP, GMFCS levels II and III participated in Study II. Data was analyzed with respect to standing ability with or without support.

Study III
3D motion analysis with simultaneous surface electromyography recording was conducted during three standing tasks: i) no-task, ii) blindfolded, and iii) attention-task, to explore the influence of visual stimuli on standing posture in TD children and in children with CP. The children with CP underwent an ophthalmological examination on a separate occasion. Thirty-six children with BSCP, GMFCS levels I to IV and 27 TD children participated in Study III. Data was analyzed with respect to standing ability with or without support in the children with CP.

Study IV
Motor function was measured with the GMFM to explore motor abilities in other positions than standing in children with CP. Timed Up and Go (TUG) test was recorded to add information about the children's walking abilities. Thirty-six children with BSCP, GMFCS levels I to IV participated in Study IV. Data was analyzed with respect to standing ability with or without support.

3.3 PARTICIPANTS

A consecutive series of 55 children with BSCP and 46 TD children was enrolled in the studies during two separate periods. The participants in Study I were recruited between 2007 and 2009, and participants for Studies II-IV were recruited between January 2012 and September 2013. Out of the 26 participants in Study I, seven children with CP also participated in Study II. All 25 children with CP in Study II participated in Studies III & IV.

The children with CP were recruited through the neuro pediatric and the pediatric orthopedic outpatient clinic at Astrid Lindgren Children's Hospital in Stockholm, Sweden.

Of the total 55 children with CP included in the four studies, 25 required support for standing. In table II, an overview of all participants is provided.

Based on their requirement of hand-held support for standing, the children with CP were divided into two groups: children standing without support will be referred to as CP-SwoS, and children standing with support will be referred to as CP-SwS. In Study I, the children in CP-SwoS were referred to as CP group A, and the children in CP-SwS as CP group B.

Table II. Overview of gender (f=female, m=males) and age (years) in all participants included in the four studies, and distribution of standing ability with (CP-SwS) or without (CP-SwoS) support, and Gross Motor Function Classification System (GMFCS) levels in the children with CP. "n" indicates number of children. TD=typically developing children.

Study	Participants	Gender (f/m)	Age; Median [min, max]	Standing Ability (n)	GMFCS Levels (n)
I	n=45				
	26 children with CP	9/17	10.5 [4.4, 16.3]	15 CP-SwoS	I:3, II:9, III:11, IV:3
	19 TD children	12/7	8.9 [5.8, 12.9]	11 CP-SwS	
II	n=25				
	25 children with CP	12/13	11.4 [7.7, 17.2]	11 CP-SwoS 14 CP-SwS	II:10, III:15
III	n=63				
	36 children with CP	16/20	11.2 [6.7, 17.2]	19 CP-SwoS	I:5, II:13, III:15, IV:3
	27 TD children	11/16	9.9 [6.5, 16.9]	17 CP-SwS	
IV	n=36				
	36 children with CP	16/20	11.2 [6.7, 17.2]	19 CP-SwoS 17 CP-SwS	I:5, II:13, III:15, IV:3

Study I: Of the 26 children with BSCP enrolled in the study, 15 children had the ability to maintain standing without hand-held support, CP-SwoS, while 11 children required hand-held support for standing, CP-SwS (Table II). In CP-SwoS, three children were classified at GMFCS level I, nine at level II, and three at level III. In CP-SwS, eight children were at GMFCS level III, and three at level IV. Nineteen TD children constituted a reference group (Table II).

Studies II–IV: A total of 36 children with BSCP and 27 TD children performed the examinations. In Study II, 27 children with CP at GMFCS levels II to III were included (Table II). Two of these children did not complete all examinations, thus data from 25 children was analyzed. In Studies III and IV, data from all 36 children with CP was analyzed. In Study III, 27 TD children constituted a reference group (Table II).

Criteria for inclusion and exclusion in Studies I-IV

Inclusion criteria:

- A diagnosis of BSCP
- Ability to stand independently with or without the use of hand-held support for at least 30 seconds
- Ability to follow verbal instructions for performing the examinations

Exclusion criteria:

- Dyskinetic CP and/or presence of dystonia
- Skeletal surgery within the previous year
- Soft tissue surgery within the previous six months
- Botulinum toxin injections within the previous three months in Study I, and within the previous six months in Studies II–III.

3.4 MEASUREMENTS AND DATA COLLECTION

Several measurements were used in the four studies; an overview is presented in Table III. Each method will be presented in more detail in the following section. Data collection for Studies II, III & IV was accomplished at three different occasions. The first testing session included 3D motion analysis, surface electromyography (sEMG) recordings and muscle strength measurements, whereas the GMFM and the neuro-ophthalmological examinations were conducted at two separate occasions respectively, during a time span not exceeding two months from the first testing.

Table III. Overview of measurements presented in Studies I-IV with respect to ICF-CY domains

Measurement	Study	Body Functions & Structures	Activity & Participation	Environment
Spasticity	I, II	x		
Joint ROM[1]	I, II	x		
Motion analysis	I, II, III	x	x	
sEMG[2]	III	x		
Muscle strength	II	x		
GMFM[3]	IV		x	
TUG test[4]	IV		x	
GMFCS[5]	I, II, III, IV		x	x
Visual function	III	x		

[1]ROM=Range of motion, [2]sEMG=Surface electromyography, [3]GMFM=Gross Motor Function Measure, [4]TUG test=Timed Up and Go test, [5]GMFCS= Gross Motor Function Classification System

3.4.1 Physical examination

All children underwent a physical examination by the same examiner (CL). Spasticity was assessed in the lower limbs muscle groups by using the modified Ashworth scale [49]. The interrater reliability of the Ashworth scale has been reported to vary from moderate to good [96]. In this thesis, lower limb spasticity was reported as either present or absent. In addition, lower limb joint ROM was measured with a goniometer in standardized positions [97]. The intra-rater reliability for ROM measurements has been reported to be high, with an estimated error at 1-5 degrees in children with CP [98]. In this thesis, data was analyzed from sagittal plane ROM measurements at the hip, knee, and ankle. Lower limb contractures were defined as passive ROM less than the neutral position of a joint.

3.4.2 Motion analysis

Three-dimensional motion analysis provides objective assessment of movement patterns with good intra-rater reliability for sagittal plane data [99]. Data is collected by placing reflective markers on specific landmarks on the person's body. All 3D motion analyses were conducted by the same two experienced physiotherapists (CL and ÅB) at the Motion Analysis Laboratory at the Karolinska University Hospital, Stockholm, Sweden.

In Studies I, II & III, an eight-camera 3D motion analysis system with passive markers (Vicon MX40®, Oxford, UK) was used to measure standing posture. Two force plates (Kistler®, Winterthur, Switzerland) embedded in the floor were used to simultaneously measure ground reaction forces. A full-body biomechanical model and marker set (Plug-In-Gait, Vicon®) was used. Markers were placed on specific anatomical positions (Figure 2). The head, thorax and pelvic segment motions are described in the global coordinate frame, and the hip, knee, and ankle joints as relative angles between distal and proximal segments. Video recordings with two digital cameras were performed at the same time.

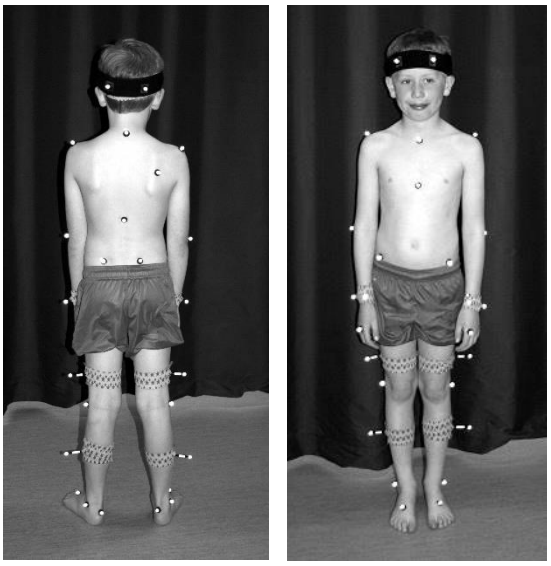

Figure 2. Marker placement during 3D motion capture (Esbjörnsson 2015). The illustration is reprinted with permission of the author.

Body position angles were described as sagittal plane angles of the head, trunk, and pelvis segments, and the hip, knee, and ankle joints, during the recorded time. Body movement ranges were described as ranges of joint movements, defined as differences between maximum and minimum angles during the recorded time. Data from the children's more weight-bearing limb as assessed through video observations in Study I and determined from force plate data during each child's no-task condition in Studies II & III, was used for analysis. Data from the right limb was used when standing asymmetry in the children with BSCP was not apparent, as well as in all the TD children.

In Study I, standing posture was recorded for 30 seconds while the children stood with their habitual shoes or orthoses on two force plates. The children who required support to achieve and maintain standing, held on to a height-adjustable horizontal bar with a slightly flexed elbow position. The children were instructed to maintain a quiet standing position.

In the children included in Studies II, III & IV, standing posture was recorded for 30 seconds during three standing tasks: a) no-task: in a self-selected standing position, b) blindfolded, and c) attention-task: while watching a video. The testing setup is illustrated in Figure 3. The video was a film sequence of a child playing with a dog, shown on a 52 x 30cm computer screen, placed 2 m in front of the child. The purpose with the video was to provide a context external to the body which required focus of attention. Short sitting breaks between the testing conditions were taken when requested. The children were tested barefoot while standing on two force plates. Those who required support held on to a horizontal bar with a slightly flexed elbow position. In Study II, data was analyzed from the no-task standing condition in the children with BSCP at GMFCS levels II and III. In Study III, data was analyzed from all three standing conditions in the children with BSCP and the TD children.

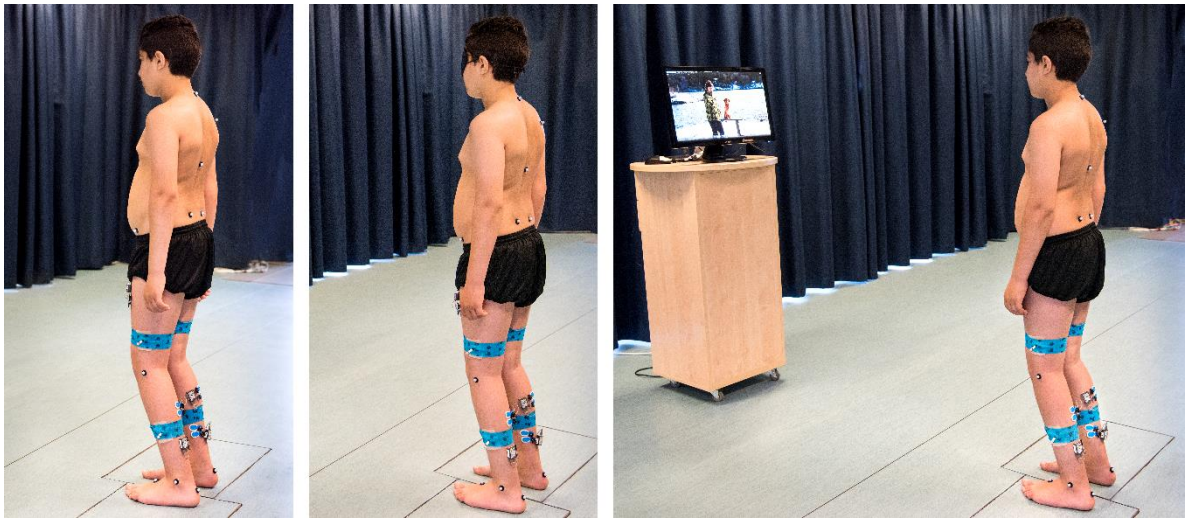

Figure 3. Illustration of testing setup during the three standing conditions: a) no-task, b) blindfolded, and c) attention-task.

3.4.3 Surface electromyography

In Study III, muscle electric activity was recorded using wireless sEMG (Noraxon®, USA) at a sample rate of 1000 Hz. sEMG electrodes (Ambu®, Denmark) were placed bilaterally on four lower limb muscles: the rectus femoris, tibialis anterior, medial gastrocnemius and soleus, according to the sEMG non-invasive assessment of muscles (SENIAM) recommendations [100] (Figure 4). Registration of muscle activity with sEMG data was collected during the entire standing procedure.

Figure 4. Illustration of the sEMG equipment.

The data was processed with EMG-designated software (ProEMG®, Prophysics, Kloten, Switzerland). The raw sEMG signal was offset to zero, and high-pass Butterworth filtered at 10Hz. Average Root mean square (RMS) was determined over a 50 ms window, and the maximum RMS value was used for further analysis. Each muscle's maximum RMS was then normalized to its corresponding value during the no-task standing condition and expressed as a percent, which allows us to examining changes in muscle activity pattern.

3.4.4 Muscle strength measurement

Muscle strength measurement by an HHD provides information about the ability to produce force at a specific muscle length. Muscle strength measurements with an HHD in the lower limbs has been reported as reliable, but deserves careful standardization of measuring positions [101; 102; 103].


Figure 5. Illustration of muscle strength measurement with an hand-held dynamometer.

In the children with CP included in Studies II-IV, isometric muscle strength was measured with an electronic HHD (Chatillon®, Greensboro, NC, USA) (Figure 5). In Study II, muscle strength data from children at GMFCS levels II and III were analyzed with respect to standing ability with or without support. In addition, data was compared with respect to two different seated conditions.

Four lower limb muscle groups were tested bilaterally: hip flexors, knee extensors, ankle dorsiflexors, and ankle plantar flexors. Lever arms were measured as the sagittal plane distance from the greater trochanter, lateral femoral condyle, and lateral malleolus to the dynamometer's placement. The strength measurements were carried out in randomized order in two seated conditions: a chair with armrests and backrest, and on a stool after removing the armrests and backrest (Figure 6). During testing the children were instructed to sit in an upright position, to not lean against the armrests or backrest, and to place their hands on their laps.

Figure 6 a) A chair with armrests and backrest, and b) a stool after removing armrests and backrest used during muscle strength measurements.

Standardized positions for testing were chosen in order to refine the children's ability to produce force and to minimize restriction from tight muscles, spasticity and/or reduced selective motor control [56]. The hip flexors and the knee extensors were tested in 90° of hip flexion and 90° knee flexion as described by Eek et al. (2006) [104]. The dorsiflexors and plantar flexors were tested in 90° of hip flexion and 30° knee flexion, and with the ankle in a neutral position (Figure 7). In the children with limited ROM in the ankle, the ankle was placed in as close to neutral position as possible.

The "make test technique" was used by encouraging the child to press as hard as possible against the dynamometer to build up strength for 4-5 seconds [56] To ensure the children's understanding of the task, a familiarization trial was performed first. A short break of about 20 s was given between the trials. The same examiner (CL) performed all measurements.

It is challenging to compare strength between children of different weights and heights. In order to obtain reliable strength values, it is recommended to calculate torque and normalize the values to weight [102]. Therefore, the force value derived from the HHD was multiplied by the lever arm, and in turn normalized to body weight.

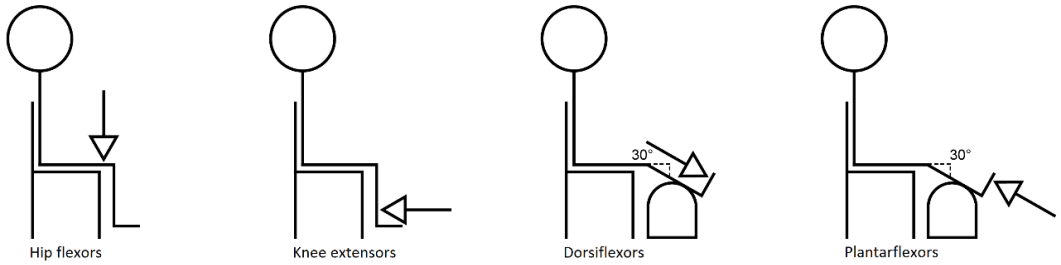

Figure 7. Test positions for isometric muscle strength measurements with a hand-held dynamometer.

3.4.5 Motor function classification

In all four studies the children's functional motor abilities in daily life were classified with the GMFCS [13; 14]. Initially, the GMFCS was developed to classify motor function in children up to 12 years of age. The classification system has been extended and revised, and nowadays covers motor function in children and adolescents up to an age of 18 years.

3.4.6 Motor function measurement

In Study IV, the children's motor function was assessed with the GMFM [42; 43], and the TUG test was recorded [105; 106].

The GMFM is an observational test that measures the children's capacity to perform motor activities in five dimensions: A) lying and rolling, B) sitting, C) crawling and kneeling, D) standing, and E) walking, running and jumping. There are two versions of the GMFM; the original GMFM including 88 items (GMFM-88), and the shorter version includes 66 items (GMFM-66). The GMFM-88 provides scores for each dimension, as well as a total GMFM-88 score. The dimension scores are calculated as a percentage of the maximum score for that dimension. The total GMFM-88 percent score is an average of the percentage scores from the five dimensions. The GMFM-66 was developed to improve scaling of the measurements, giving a hierarchical ordering of the items and a unidimensional GMFM score with interval properties by using the freely available software, Gross Motor Function Ability Estimator [43]. In Study IV, both the GMFM-88 and the GMFM-66 were used. With the GMFM, the children's total GMFM-88 percent score, percent scores for each GMFM-88 dimension (A-E), and GMFM-66 score were calculated. The GMFM was measured during play in a standardized environment familiar to the child in cooperation with the physiotherapist from the children's habilitation center on a separate occasion. The children were tested without shoes, orthoses, or walking aids.

Walking capacity in the children using a mobility device could not be assessed with the GMFM, as most of the items included in the walking dimension required the ability to walk with arms free. Therefore, in Study IV, the children's functional mobility in walking was measured with the TUG test. The test is a valid, reliable, and widely used performance-based measure of functional mobility in walking in adults and children [105; 106]. A sequence of sit-to-stand, walk 3 m, turn 180 degrees, and return to stand-to-sit tasks is timed during the TUG test.

3.4.7 Neuro-ophthalmological examination

The children with BSCP included in Studies II-IV underwent a neuro-ophthalmological examination by an ophthalmologist at the Karolinska University Hospital, Stockholm, Sweden, on a separate occasion. Binocular visual acuity with visual charts at 3 m was categorized as either normal/near to normal (>0.33 in decimal value) or moderate/severe/blind (<0.33 in decimal value) [107; 108]. Visual field was evaluated with either the Stycar ball test, in which the patient reported when a white three cm diameter ball first became visible as it was moved inward from beyond the boundary of each quadrant of the visual field, or with the kinetic manual Goldmann Perimetry, documented as normal, hard to assess, or reduced [109; 110]. The evaluation instruments were chosen based on each child's ability to participate. Furthermore,

oculomotor function was assessed by evaluating saccadic movements as normal or dysmetric, smooth pursuit movements as normal or altered, and for detecting strabismus, as present or absent. Fixation was qualitatively assessed as good or unstable. Smooth pursuits and saccadic eye movements serve to shift the direction of gaze towards new targets or movements, whereas fixation serves to stabilize gaze when the head is moving. In Study III: Table I, visual impairment from the ophthalmological examination in the children with BSCP is presented.

3.4.8 Statistical methods

Statistical analyses were carried out using commercially available software (SPSS, Chicago, IL, USA). The significance level was determined at the $p < 0.05$ level. An overview of statistical methods used across the four studies is provided in Table IV.

Non-parametric statistical tests were used to determine differences in characteristics between and within the groups in Studies I, II, III & IV, body position angles and body movement ranges during standing in Study I, body position angles and muscle strength in Study II, and GMFM scores in Study IV.

Parametric statistical tests were used to determine differences in body position angles and body movement ranges during the no-task standing conditions among the three groups, to evaluate the influence of vision on body position angles and body movement ranges, and muscle activity within groups with the no-task condition as each child's own reference in Study III.

Table IV. Overview of statistical methods used in Studies I-IV.

Statistics	Study I	Study II	Study III	Study IV
Frequency: number, percentage	x	x	x	x
Median [min, max]	x	x		x
Mean (SD)			x	
Kruskal-Wallis test	x			x
Mann Whitney U test	x	x		x
Wilcoxon signed rank test	x	x		
Chi-square test	x	x	x	x
One-way ANOVA			x	
Bonferroni post-hoc test			x	
Paired *t*-test			x	

4 ETHICAL CONSIDERATIONS

All studies were approved by the Regional Ethical Review Board in Stockholm, Sweden, and conducted in accordance with the Declaration of Helsinki. All children and parents were given verbal information. Parents and the children 10 years or older were also given written information. Informed consent to participate was obtained verbally from the children, and in writing from the parents.

5 RESULTS AND DISCUSSION

The main finding from Studies I, II, III, and IV are summarized in this section. The results from physical examination, muscle strength measurements, 3D motion analysis, muscle activity recording, and motor function measurements are presented with respect to children's standing ability, with or without support (Figure 8), followed by a discussion about similarities and differences with respect to the standing ability groups. Detailed results of each study are provided in the publications and manuscripts.

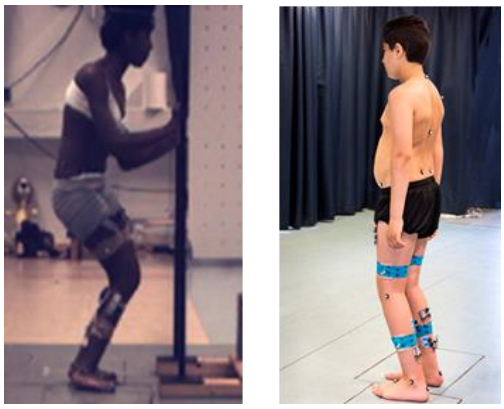

Figure 8. A representative child a) requiring support for standing (CP-SwS), and b) standing without support (CP-SwoS.

5.1 STANDING ABILITY AND MOTOR FUNCTION IN THE VARIOUS GROUPS

Overviews of results from all studies are presented. Table V presents spasticity, joint contractures and joint ROM in the children in Studies I, II and III & IV. Table VI presents muscle strength in the lower limbs in Studies II and III & IV, and Table VII presents standing posture in the children in Studies I, II, and III & IV.

5.1.1 Children standing without support

In the CP-SwoS group, spasticity in the plantar flexors and knee flexors was present in almost all children, while spasticity in the hip flexors was less frequent. During physical examination, the hip, knee and ankle could be extended to at least neutral position even though ROM varied (Table V). Muscle strength values revealed muscle weakness in the lower limbs (Table VI).

Table V. Overview of spasticity, contractures, and passive joint range of motion (ROM) in degrees (°) in the more weight-bearing limb in children with CP, standing with (CP-SwS) or without (CP-SwoS) support in Studies I, II, and III & IV. A Chi-square test was used to determine differences in presence of spasticity and contractures, and a Mann Whitney U test was used to determine differences in ROM between the groups in the various studies ($p<0.05$).

	Study I n=26					Study II n=25					Studies III-IV n=36				
	CP-SwoS	n	CP-SwS	n	*p*	CP-SwoS	n	CP-SwS	*n*	*p*	CP-SwoS	n	CP-SwS	*n*	*p*
		15		11			11		*14*			19		*17*	
Spasticity, uni- or bilateral[1]															
Hip flexors	3	15	6	11	0.103	1	11	2	13	1.000	1	19	2	16	0.582
Knee flexors	12	15	11	11	0.238	10	10	14	14	NA	17	18	16	17	1.000
Plantarflexors	14	15	10	11	0.423	11	11	14	14	NA	19	19	17	17	NA
ROM median [range]°															
Hip extension	0 [-10[2], 10]	15	0 [-15, 0]	11	**0.041**	0 [-15, 10]	11	0 [-15, 5]	14	0.267	0 [-15, 10]	19	0 [-15,-5]	17	0.165
Knee extension	0 [-10[3], 10]	15	-10 [-30, 0]	11	**0.001**	5 [-15, 10]	11	-10 [-25, 10]	14	**0.025**	5 [-15, 15]	19	-10 [-25, 10]	17	**0.003**
Ankle dorsiflexion	10 [-10[4], 20]	15	0 [-15, 35]	11	**0.009**	0 [-5, 10]	11	10 [-5, 20]	14	0.267	5 [-5, 15]	19	5 [-30, 20]	17	0.925
Joint contractures, uni- or bilateral[1]															
Hip flexion	2	15	5	11	0.095	4	11	8	14	0.428	7	19	8	17	0.736
Knee flexion	5	15	9	11	**0.021**	4	11	11	14	**0.049**	7	19	12	17	0.054
Plantarflexion	1	15	2	11	0.556	5	11	5	14	0.697	5	19	6	17	0.721

[1]nr of children, [2] (-) Hip flexion contracture, [3](-) Knee flexion contracture, [4](-) Plantarflexor contracture, defined as passive ROM less than the neutral position of a joint

Table VI. Muscle strength in children with CP standing with (CP-SwS) or without (CP-SwoS) support included in Studies II-IV. A Mann-Whitney *U* test was used to determine differences between the groups in the various studies (p<0.05).

	Study II n=25					Studies III-IV n=34				
	CP-SwoS	n	CP-SwS	*n*	*p*	CP-SwoS	n	CP-SwS	*n*	*p*
		11		*14*			17		*17*	
Muscle strength, median [range] (Nm/kg)										
Hip flexors	0.86 [0.5, 1.34]	11	0.83 [0.50, 1.68]	14	0.767	0.90 [0.57, 1.81]	15	0.80 [0.50, 1.68]	17	0.411
Knee extensors	0.62 [0.41, 1.04]	11	0.95 [0.51, 1.31]	14	**0.038**	0.89 [0.41, 1.38]	15	0.94 [0.51, 1.31]	17	0.295
Dorsiflexors	0.16 [0.00, 0.30]	10	0.17 [0.09, 0.33]	13	0.976	0.20 [0.00, 0.39]	14	0.17 [0.07, 0.33]	15	0.234
Plantar flexors	0.17 [0.00, 0.23]	9	0.17 [0.09, 0.28]	13	0.431	0.19 [0.00, 0.39]	13	0.17 [0.09, 0.28]	15	0.683

From motion analysis during the children's habitual standing condition, on a group level, the children stood with an upright head position, slight anterior trunk tilt, anterior pelvis tilt, approximately 20° of hip flexion, 10-15° of knee flexion, and almost 10° of ankle dorsiflexion. The body movement ranges of the segments and joints were around 20° at the head and 5° at the trunk, hip, knee and ankle (Table VII, Studies I & II & III). The children stood with more flexion than their potential passive joint extension ROM (Study I: Figure 2). While blindfolded, the habitual body position was unchanged, the head was more still, and posture was adapted to the new environmental demands by increased calf muscle activity only. Moreover, the use of visual stimuli improved posture; while watching the film, in the attention-task, the children stood more still and with less lower limb muscle activity compared to the no-task standing condition (Study III; Table II).

The children's gross motor function capacity accomplished by the GMFM-88 reached almost 90% of the total score. The GMFM dimension scores reached almost 100% in A (lying and rolling), B (sitting), and C (crawling and kneeling) respectively, and above 70% in D (standing) and E (walking, running and jumping) respectively (Table VIII). With the GMFM-66 the children achieved a score of around 70 of a maximum score 100. The TUG test, was completed in approximately 11 s (Study IV).

Table VII. Overview of standing posture (body position and body movements) during the no-task standing condition in children with CP standing with (CP-SwS) or without (CP-SwoS) support in Studies I, II, and III. It is worth noting that children were tested with their habitual shoes and orthoses in Study I, while they were barefoot during testing in Studies II & III. A Mann-Whitney *U* test was used to determine differences between the groups in the various studies (p<0.05).

	Study I n=26			Study II n=25			Study III n=36		
	CP-SwoS (n=15)	CP-SwS (n=11)	*p*	CP-SwoS (n=11)	CP-SwS (n=14)	*p*	CP-SwoS (n=19)	CP-SwS (n=17)	*p*
Body position angles degrees, median [min, max]									
Head				1 [-17[1], 20]	-1 [-18, 26]	0.839	-4 [-33, 28]	1 [-18, 26]	0.616
Trunk	2 [-7[2], 26]	12 [-15, 34]	0.122	2 [-6, 19]	19 [4, 36]	**<0.001**	2 [-8, 19]	18 [4, 36]	**<0.001**
Pelvis	16 [-2[3], 29]	13 [-10, 25]	0.357	18 [3, 27]	13 [-13, 21]	0.095	15 [3, 27]	13 [-16, 29]	0.107
Hip[d]	18 [7, 32]	31 [-2[4], 54]	**0.040**	22 [0, 33]	26 [1, 49]	0.222	20 [-1, 33]	22 [1, 49]	0.129
Knee[e]	17 [-6[5], 47]	45 [28, 95]	**<0.001**	12 [-18, 70]	46 [15, 76]	**0.001**	10 [-19, 70]	45 [0, 76]	**<0.001**
Ankle[f]	13 [0, 33]	9 [-19[6], 58]	0.659	7 [-6, 20]	15 [-16, 45]	0.536	8 [-6, 24]	14 [-16, 45]	0.827
Body movement ranges degrees, median [min, max]									
Head				18 [7, 68]	26 [12, 110]	0.107	16 [7, 68]	28 [12, 110]	**0.006**
Trunk	6 [1, 18]	8 [1, 26]	0.138	6 [3, 18]	10 [3, 29]	0.085	7 [3, 23]	10 [3, 29]	**0.021**
Pelvis	2 [0, 7]	4 [2, 11]	**0.012**	3 [1, 8]	5 [2, 11]	0.075	4 [1, 8]	5[2, 14]	**0.030**
Hip	5 [1, 15]	9 [4, 21]	**0.013**	6 [2, 17]	6 [3, 15]	0.467	6 [2, 17]	7 [3, 27]	0.257
Knee	4 [1, 13]	9 [6, 21]	**0.001**	7 [2, 20]	12 [5, 22]	0.166	7 [2, 20]	12 [5, 22]	**0.009**
Ankle	2 [1, 9]	3 [1, 13]	0.474	4 [2, 7]	7 [1, 16]	**0.011**	4 [2, 7]	7 [1, 16]	**0.001**

[1](-) head extension, [2](-) trunk extension, [3](-) posterior pelvis tilt, [4](-) hip extension, [5](-) knee extension, [6](-) plantar flexion

Table VIII. Gross Motor Function Measure-88 (GMFM-88) presented as median [min, max] total score (%) and dimension scores (%) in the children with CP standing with (CP-SwS) or without (CP-SwoS) support. A Mann-Whitney *U* test was used to determine differences between the groups (p<0.05).

GMFM-88	CP-SwoS n=19	CP-SwS n=17	*p*
Total score	88 [64, 100]	70 [37, 81]	**<0.001**
A) Lying & Rolling	98 [84, 100]	96 [90, 100]	0.271
B) Sitting	100 [90, 100]	98 [65, 100]	0.285
C) Crawling & Kneeling	98 [19, 100]	93 [19, 98]	**0.035**
D) Standing	80 [59, 100]	31 [5.1, 82]	**<0.001**
E) Walking, Running & Jumping	72 [42, 99]	22 [0, 50]	**<0.001**

5.1.2 Children standing with support

In the CP-SwS group, spasticity in the plantar flexors and knee flexors was present in almost all children, while spasticity in the hip flexors was less frequent (Table V). During physical examination, the hip, and ankle could be extended to at least neutral position, and the knee to an almost neutral position even though ROM varied (Table V). Muscle strength values revealed muscle weakness in the lower limbs (Table VI).

From motion analysis during the children's habitual standing condition, on a group level, the children stood with an upright position of the head, 10-20° of an anterior trunk tilt, anterior pelvis tilt, around 25° of hip flexion, 45° of knee flexion, and 10-15° of ankle dorsiflexion. Moreover, they stood with a substantial body movement ranges of the segments and joints: 25-30° at the head, 10° at the trunk and at the knee, 5-10° at the hip, and 5° at the pelvis and at the ankle (Table VII). The children stood with more flexion than their potential joint extension ROM (Study I: Figure 2). While blindfolded, the body position was more flexed, the quadriceps muscle activity increased, and there was a tendency for less calf muscle activity compared to the no-task condition. The use of visual stimuli improved head position: while watching the film in the attention-task, the children stood with the head in a more upright and still position, compared to the no-task standing condition (Study III; Table II).

The children's gross motor function capacity accomplished by the GMFM-88 reached 70% of the total score. The GMFM dimension scores reached almost 100% in A and B respectively, just above 90% in C, and below 30% in D and E respectively (Table VIII). With the GMFM-66 the children achieved a score of almost 55 of a maximum score 100. The TUG test was completed in approximately 26 s (Study IV).

5.1.3 Typically developing children

From motion analysis during the children's habitual standing condition the TD children stood with an erect body position with an upright position of the head, slightly extended trunk, anteriorly tilted pelvis, slightly flexed hip, somewhat hyperextended knee and nearly neutral ankle. Furthermore, they stood still with only minor body movement ranges of the head, trunk, pelvis, hip, knee and ankle (Study I: Table 1). Without vision as support, i.e. while blindfolded, the habitual standing posture was maintained and posture was adapted to the new environmental demands by increased calf muscle activity only. The intensified visual stimuli of watching a short movie sequence did not alter posture compared to the no-task standing condition (Study III; Table II). The TUG test was completed in approximately 8 s. (Study IV).

5.2 SIMILARITIES AND DIFFERENCES BETWEEN THE GROUPS

There were evident similarities and differences in motor function between children with the heterogeneous condition of BSCP, at GMFCS levels I to IV with different standing abilities that are addressed below.

5.2.1 Physical examination

During physical examination the hip and ankle could be extended to at least neutral position and the knee to an almost neutral position in all children with CP. Contractures at the hip and ankle were present to an equal extent in both groups of children, but more frequently at the knee in CP-SwS (Table V). Furthermore, spasticity in the lower limbs was present to an equal extent in both groups of children (Table V).

Biomechanical constraints could not be considered explain the variety in motor function in standing in the children with CP. The findings are in accordance with previous studies by Vos et al. (2016) who reported low correlation between decreased ROM and motor development [64]. Furthermore, Gorter et al. (2009) reported that spasticity was only marginally related to gross motor function development in young children with CP, and Ross et al. (2007) reported that spasticity explained only a small amount of the variance of motor function between children with BSCP who ambulated with or without assistive device [51; 52]. Additional measurements are required to more fully comprehend motor function difficulties in activities such as standing.

5.2.2 Muscle strength

The need for support when standing in the children with CP-SwS might raise the question of whether difficulties during standing originate from muscle weakness. Therefore, muscle strength was measured with an HHD in the children included in Studies II, III & IV. The findings indicate that the children who required hand-held support were *not* weaker in the lower limb muscle groups compared to those who stood unsupported (Table VI). Interestingly, the children with CP were practically equally strong despite their varying standing abilities.

In Study II, muscle strength data from children functioning at only GMFCS levels II and III was analyzed in relation to their ability to stand with or without support. The children in the two groups were equally strong in their hip, and ankle joint muscles. Unexpectedly, the children in CP-SwS were found to be stronger in the knee extensors than those in CP-SwoS, despite the crouched body position and the requirement for support, (Table VI, Study II; Fig.2). To explore whether the children's ability to produce force was influenced by seated conditions, muscle strength was measured in two different seated conditions: in a stable sitting position on a chair, and in a more demanding sitting position on a stool. There were no differences in muscle strength between the seated conditions in either CP-SwS or CP-SwoS (Study II).

The finding that lower limbs muscle strength could not explain the difference in standing ability between children functioning at GMFCS levels I to IV has, to our knowledge, not been previously reported. In reported literature, it is well recognized that children with CP are substantially weaker in the lower limb muscles than TD children. In the children included in Studies II, III & IV, the strength values obtained correspond to previously reported values by Dallmeijer et al. (2011) [111]. Therefore, it is likely that the children with CP were in fact weaker in the lower limb muscles than the TD children, even though it was not measured. Previously, muscle strength has been related to differences in balance, measured as postural sway, between children at GMFCS levels I and II in a study by Lowes et al. (2004) [73]. In addition, muscle strength has been related to walking ability with or without support with respect to GMFCS levels [51; 58]. Children who walk independently in all environments at GMFCS level I were reported to be stronger in most lower limb muscle groups than children with more limited walking abilities at levels II and III [58; 87; 88]. Whether the children who walk without an assistive device at GMFCS level II really are stronger in the lower limb muscles than the children who walk with an assistive device at level III is not that clear. Similar to our findings, there are several studies that have reported on equally strong knee extensors, in children functioning at GMFCS levels II as in those functioning at level III [58; 87; 88]. In the previously mentioned studies, the hip extensors were also reported as equally strong in children functioning at level II and III, whereas the hip abductors were weaker in the children functioning at level III.

5.2.3 Standing

The children who stood unsupported – both the TD children and the children in CP-SwoS – fulfilled the requirements for postural orientation during standing. They thereby had the ability to align and maintain their body position with respect to both gravity and the environment. This contrasts with the children in CP-SwS.

On a group level, all children with CP stood in a crouched body position compared to the TD-children during the habitual standing condition (Study I & Study III). The children in CP-SwS stood in a more pronounced crouched position and with a considerable amount of body movements between the segments and joints than the children in CP-SwoS, despite their use of hand-held support (Table VII). All children with CP stood with more flexion than their potential lower limbs joint extension ROM, more pronounced in CP-SwS (Study I; Figure 2).

Motor disorders could not explain the support for standing or the greater knee flexion during standing in the children in CP-SwS compared to in CP-SwoS, as spasticity and muscle

weakness were present to an equal extent in both groups of children. The inability to stand unsupported and the flexed body position indicate that sensory disturbances and/or perceptual impairments may disrupt motor function ability in upright positions on the feet in children who require support for standing.

The children's difficulties to stand still relative to gravity in CP-SwS, indicate proprioception disturbances with difficulties to sense movements of the limbs, both in and between the body segments, and the relative position of the body segments in space. Disturbed proprioception has been previously reported in children with CP in a study by Wingert et al. (2009) [78]. Moreover, Damiano et al. (2013) reported that proprioceptive deficits were related to instability in standing and to decreased walking speed in children with mild CP, and Bartonek et al. (2016) suggested that disturbed sensory information from the lower limbs contributed to decreased walking velocity in children with BSCP requiring assistive device for walking in a recently published study[29; 94]. It is likely that proprioceptive disturbances were present and influenced standing in the CP-SwS group in our studies.

In Study I, another interesting finding is that the children with CP did not fully extend their joints to use their full joint ROM during standing. The knee could be passively extended on the examination table to an almost neutral position in both groups, but the children stood with an apparent knee flexion, even more so in the CP-SwoS group, when faced with the challenge of resisting gravity (Study 1: Figure 2). Previously, difficulties extending the legs to produce antigravity reactions during standing have been reported to be an indication of perceptual disturbances with difficulty detecting gravity [95]. The apparent knee flexion during standing observed in children in both our CP-SwoS and CP-SwS groups indicates that they have difficulty to detect gravity as a reference. Another indication of perceptual disturbances in perceiving the body position in space, is the finding that the children in CP-SwS could maintain standing for at least 30 s with the use of hand-held support. Previously, cutaneous input from the hands has been reported to provide a reference frame external to the body, which may help compensate for perceptual impairments and improve standing and walking [24].

5.2.4 Influence of vision on standing

The visual function of children with CP included in Studies II, III & IV was assessed through an examination by an ophthalmologist. Neuro-ophthalmological impairments were found in almost 90% of the children, regardless of their standing ability. Visual acuity was considered sufficient to see the film during the attention-task in all children included in the analysis (Study III: Table I).

In Study III, standing posture was investigated in the presence of three different visual stimuli – in the usual laboratory setting: no task, blindfolded, and while watching a short movie: attention-task – to explore the influence of visual stimuli on posture in children with CP and TD children (Study III; Table II). An illustration of standing posture, described as body position angles and body movement ranges during three standing conditions, is provided in Figure 9.

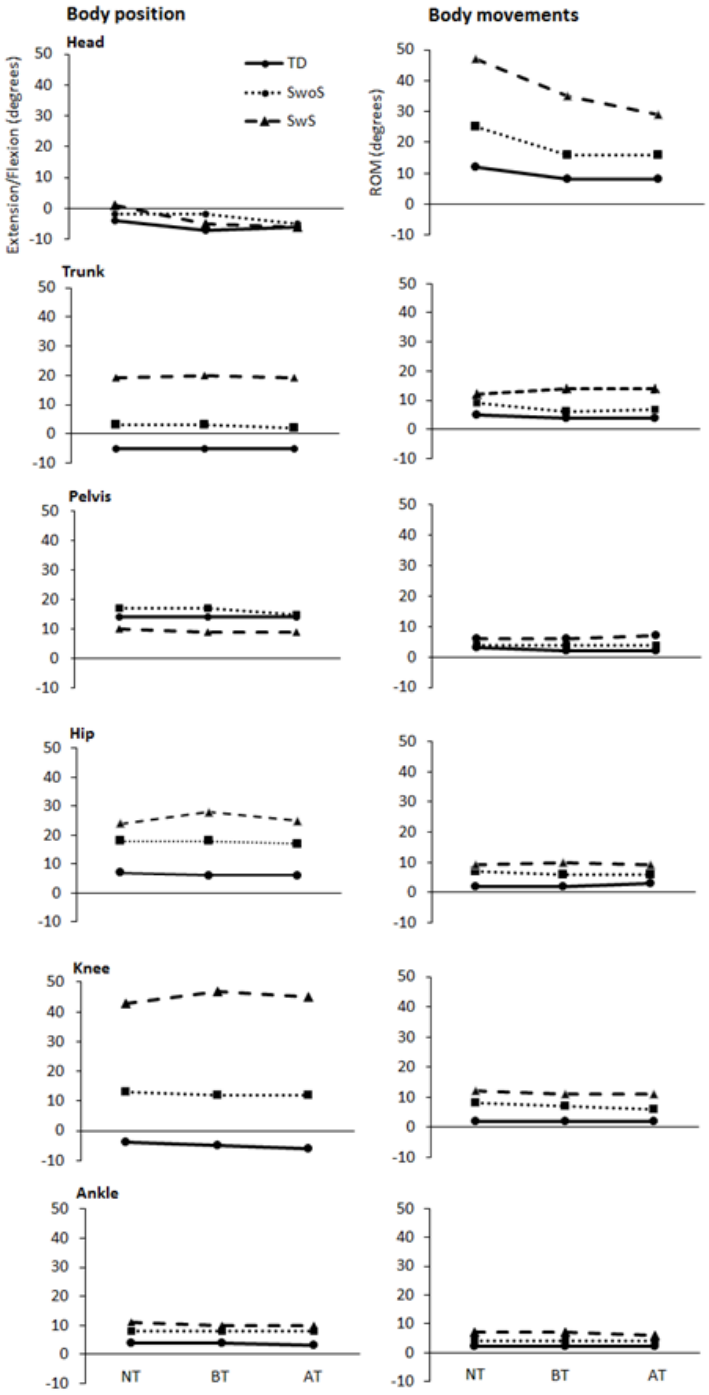

Figure 9. Illustration of mean sagittal plane body position angles and body movement ranges in degrees during three standing conditions: no task (NT), blindfolded (BT) and attention-task (AT) in typically developing (TD) children, and in children with CP standing with (SwS) or without (SwoS) support.

The task of standing blindfolded was considered to be demanding for all children. While blindfolded, the children who stood unsupported, both the TD children and children in CP-SwoS, adapted their posture by increasing muscle activity around the ankle only. Thus, a combination of somatosensory and vestibular input ensured postural orientation in the children who stood unsupported, even without visual input [20]. Contrastingly, the children in CP-SwS were *more* dependent on external visual cues for posture during standing; while blindfolded, the already flexed body position became even more flexed and muscle activity increased in the knee extensors, despite the somatosensory input from the hand-held support (Study III; Table II).

Vision provides a reference frame external to the body, based on cues in the near environment that may help compensate for possible disturbances in the somatosensory or vestibular systems during quiet standing [21; 24]. Loss of proprioception in the CP-SwS group most likely contributed to the reduced ability to maintain postural alignment while blindfolded. This finding is in accordance with Damiano et al. (2013) who reported that proprioceptive disturbances were linked to instability in standing in some children with mild CP [29]. Since the blindfolded standing was considered provocative for the children's standing ability in Study III, the increased quadriceps muscle activity in the CP-SwS group could be an indication of co-contraction caused by perceptual impairments. This finding is in accordance with Ferrari et al, attributed a blocked rigid posture, called freezing of posture, during provoking activities, to perceptual impairments [93].

The task of watching a short movie provided a focus for attention external to the body. The TD children could watch the movie without any alterations in posture. By viewing the film, posture was aided in the children in CP-SwS. They stood more still and muscle activity decreased in the calf muscles (Study III; Table II and Figure 2). The finding that visual cues external to the body seemed to assist posture correspond to results from Donker et al., who reported that visual stimuli improved posture in children with unilateral CP [31]. In our study the presence of an intensified visual stimuli assisted posture to some extent in the children who could better integrate sensory information. They adapted their posture to new environmental demands with muscle activity. This finding indicates that impaired proprioception most likely was present even in the children with milder CP, in accordance with the study by Wingert et al. (2009) [78].

The finding that visual input influenced standing posture differently depending on standing ability strengthens the hypothesis that impairments in the sensory systems contributed to standing difficulties in the children with CP. Difficulties with spatial orientation, more specifically in perception of the environmental vertical reference, can be one possible sensory disturbance that contributes to the increase dependence on external cues such as vision and cutaneous input from the hands for standing in some children.

Vision is not only important for overall body position, but also for the position of the head. In Study III, during the habitual standing condition, all children with CP stood with a considerable amount of head movements, which was more obvious in the children in the CP-SwS group (Table IV). Moreover, the head position seemed to be maintained more easily both while blindfolded and while watching the video compared to during the no-task condition (Study III; Table II). In a study by Saavedra et al. (2010) that investigated head stability during quiet sitting

while vision was manipulated, it was found that children had difficulties in stabilizing the head, and that deficits worsened when the children were asked to close their eyes [112]. In Study III, both the blindfolded task and the attention-task must be considered to require increased somatosensory and visual focus of attention which may explain the quieter head position. Difficulties stabilizing the head might indicate impairments in the vestibular system, which has important sensory functions, contributing to perception of self-motion, head position, and spatial orientation relative to gravity [22]. The role of vestibular function for balance and movement has only sparsely been studied in children with CP, and more research in the field has been solicited in a recently published study by Berthoz et al. (2015) [23].

5.2.5 Motor function

In order to explore whether the ability to stand without support could be related to performing motor activities in positions on the floor (lying), to gradually more upright positions, and finally to walking in children with CP, motor capacity was assessed with the GMFM.

To get an overall comprehension of the children's motor ability the total GMFM-88 score was calculated in Study IV. About 30% of the items included in the test require unsupported standing or walking ability, and thereby could not be fulfilled by the children who required support to stand. As such, the total GMFM-88 score was lower in the CP-SwS group than in the CP-SwoS group (Table VII).

By using the GMFM-88, the children's motor abilities in the five dimensions (A to E) could be analyzed as a complement to the total GMFM-88 score [41]. From the GMFM-88 dimension scores, we found practically no discrepancies in gross motor function abilities between the children in the CP-SwS and CP-SwoS groups, in positions close to the floor, but large discrepancies arose in positions that required maintenance of upright standing on the feet. In the dimensions that measured standing and walking activities, the children in the CP-SwoS group reached above 70% of the full scores, while the children in the CP-SwS group only reached around 30%. In the dimensions crawling and kneeling (C), sitting (B) and lying (A), children in both CP-SwoS and CP-SwS groups, reached more than 90% of the full scores. All children had a remarkably similar ability to perform the requested motor tasks, even though there was a large heterogeneity among the children (Table VIII).

The children in CP-SwS were able to maintain posture in static positions and to perform dynamic movements in the direction of gravity to a good amount in positions other than standing. These children achieved sitting on a bench, crawled, attained high kneeling, and even walked on their knees, even though they require support when faced with the challenge of resisting gravity while standing. All named tasks require not only reasonable muscle strength, but also motor control and postural control, and can be regarded as rather complex motor tasks. During kneeling in particular, the children who require support to stand were sufficiently strong in performing complex motor activities in positions that offered a wide base of support. The observation that motor function difficulties can arise in an upright position on the feet has been reported previously. For example Brogren et al. (2001) reported that the children with different abilities to walk had similar abilities to perform motor tasks while sitting [91].

In another study Tieman et al. (2007) reported that some children preferred to crawl despite their ability to walk [47]. More recently, Begnoche et al. (2016) reported that achievement of postural control in sitting or reciprocity in crawling were not good predictors for walking ability in young children with CP [44]. These authors furthermore reported functional strength and dynamic postural control, measured as the ability to attain sitting and standing from a chair, to be a good predictors for walking ability [44].

That children in CP-SwS move around unhindered on the floor and function well in sitting position indicates that impairments in the sensory systems contribute to standing difficulties in the CP-SwS group. Previously somatosensory disorders have been associated with difficulties during standing and walking in children with BSCP [29; 94]. In Study IV, the children might use sensory information from the ground in positions such as lying, sitting and high kneeling to compensate for possible sensory disturbances. Cutaneous information from the hands have been reported to aid standing and walking with support by providing a reference frame external to the body [24]. Cutaneous input might serve as an external reference frame that supports the sensory motor system to produce movements while moving around on the floor or in high kneeling in the children in CP-SwS. Cutaneous information from the hands serves the same purpose during standing with support [24]. Thus, the children's difficulties generating and guiding movements in positions that require spatial orientation may be caused by perceptive disturbances. In a previous study Ferrari et al. reported that motor function was strongly influenced by errors in analyzing information from the surrounding space, from the body position and from produced and received movements in some children with BSCP [38].

5.3 METHODOLOGICAL CONSIDERATIONS AND LIMITATIONS

Motor development in CP is commonly investigated from a GMFCS perspective, which provides an overall picture of a child's motor performance in daily life activities [13; 14; 113]. In this thesis, standing posture in children with BSCP was examined from the perspective of executing the task of standing in a laboratory setting. The present work was not intended to investigate standing function in daily life situations.

The first pilot assessments in studies II-IV include investigation of standing posture in environments providing different external spatial reference frames, ranging from a narrow space while holding on, to gradually more challenging environments with no support or nearby reference frames, in an attempt to examine the importance of external visual and somatosensory input in all children, both TD and with BSCP. It soon became clear that it was not feasible or meaningful to test children who stood unsupported in many conditions.

In Study III, the no-task situation in CP-SwS and CP-SwoS/TD groups can in some sense be considered as different conditions, as one incorporates somatosensory input from the cutaneous sensors in the hands, and one does not. It would have been ideal to collect standing with support data on all children in order to compare identical conditions. As such data was not available, care has been taken in this thesis to interpret the relevant results with regards to differences and similarities in motor behavior within the two groups of children with the heterogeneous diagnosis of BSCP, rather than as between-group differences. Furthermore, as the laboratory

was only equipped with two force plates, it was not possible to measure the amount of hand-held support required by the children in the CP-SwS group.

Measuring muscle strength in children is challenging [114]. This is particularly true for children with CP who, in addition, have both motor control deficits, and motor disorders such as spasticity, co-contraction and tight muscles, which are all considered to influence selectivity [56; 68; 115]. Nonetheless, measuring muscle strength with an HHD is a commonly used method in clinical practice, largely due to its relative feasibility compared to other dynamometry techniques. Several studies have reported on different strength measurements depending on children's testing positions [88; 103]. In this thesis, the testing positions were chosen in order to, as much as possible, reduce the influence of spasticity in the antagonist muscles, poor SMC and/or tight muscles of the above-mentioned difficulties. The positions were furthermore standardized as much as possible.

Muscle strength was measured in two different seated conditions, in a secure sitting position on a chair with armrests and backrest as well as in a more insecure position on a stool, in an effort to explore whether spatial security influenced for the ability to produce force. In Study II, no differences in force production between the two conditions were detected. Most likely, the children with possible perceptual impairments had adopted compensatory strategies to avoid an expected feeling of insecurity, and were seated in a crouched position. To trigger possible perceptual impairments such as for example, a startle reaction, a test protocol which provokes balance by perturbing the children's center of mass outside of the base of support would have been a useful complement in Study II. In a previous study by Ferrari et al. (2010) in which higher demands were placed on subjects by provoking stability limits in a sitting position, decreased ability to perform a reaching task was reported in children with perceptive impairments than in those without [38].

Sample size of the study groups was small, and statistical sub analyses with even smaller groups were performed, which limits generalizability to other children with BSCP.

6 CONCLUSIONS AND CLINICAL IMPLICATIONS

- Investigation of standing posture verified a crouched body position during standing which was more obvious in the children who required hand-held support to stand, representing almost half of the particpants in the study.

- Muscle strength measurements indicated that the children in both groups were equally strong in the lower limb muscle groups despite their variation in standing abilities.

- Gross motor function measurements indicated that the children who could not stand without support were as capable to perform motor activities in lying, sitting and kneeling positions as the children who stood unsupported.

- Vision influenced posture differently depending on the children's standing ability. During the attention demanding task, the children who stood unsupported stood more still and with less lower limb muscle activity. While blindfolded, they adapted their posture to the environmental change by activating muscles around the ankle with no changes in overall body position. In contrast, the children who required hand-held support to stand used another strategy; the already flexed body position became even more flexed, and muscle activity increased in the knee extensors while blindfolded, despite the use of external support.

Motor disorders could not explain the support for standing or the crouched body position during standing, as children in both groups were equally strong in the lower limb muscles, and motor function abilities were rather similar in positions with no requirement of standing on the feet opposing gravity.

The crouched body position and the reduced ability to maintain posture while blindfolded indicate proprioception deficits in the children who required support. The increased quadriceps muscle activity could be an indication of compensatory co-contraction caused by perceptual impairments. That motor function difficulty arises in a standing position opposing gravity indicates that standing difficulties may be attributable sensory and/or perceptual disturbances.

Consideration to possible sensory disturbances and their influence on motor function should be given during clinical planning and decision-making to ensure not hampering the children's solutions of organizing their standing and walking abilities. Furthermore, this knowledge should be transferred to other situations in the child's environment to make mobility as enjoyable and useful as possible to the child.

7 FUTURE PERSPECTIVES

In this work motor difficulties could be identified by using accessible measurement tools. The methods used did provide indications that possible sensory and/or perceptual disturbances might influence motor function. There are only few instruments feasible to differentiate motor disorders from sensory disturbances in children with CP. Future efforts are solicited to further develop relevant methods and identify signs that detect sensory disturbances and their consequences on motor function in children with the complex movement and posture disorder of CP.

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9 REFERENCES

1. Shumway-Cook A, Woollacott MH (2012) Motor control : Issues and theories. In *Motor control : translating research into clinical practice*, 4th ed., pp. 3-20. Philadelphia: Wolters Kluwer Health/Lippincott Williams & Wilkins.

2. World Health Organization (WHO) and WHO Workgroup for Development of ICF for Children and Youth. International Classification of Functioning D, and Health - Version for Children and Youth: ICF-CY (2007).

3. Rosenbaum P, Paneth N, Leviton A *et al.* (2007) A report: the definition and classification of cerebral palsy April 2006. *Dev Med Child Neurol Suppl* **109**, 8-14.

4. Westbom L, Hagglund G, Nordmark E (2007) Cerebral palsy in a total population of 4-11 year olds in southern Sweden. Prevalence and distribution according to different CP classification systems. *BMC Pediatr* **7**, 41.

5. Oskoui M, Coutinho F, Dykeman J *et al.* (2013) An update on the prevalence of cerebral palsy: a systematic review and meta-analysis. *Dev Med Child Neurol* **55**, 509-519.

6. Himmelmann K, Uvebrant P (2014) The panorama of cerebral palsy in Sweden. XI. Changing patterns in the birth-year period 2003-2006. *Acta Paediatr* **103**, 618-624.

7. Sellier E, Platt MJ, Andersen GL *et al.* (2016) Decreasing prevalence in cerebral palsy: a multi-site European population-based study, 1980 to 2003. *Dev Med Child Neurol* **58**, 85-92.

8. Barkovich AJ, Guerrini R, Kuzniecky RI *et al.* (2012) A developmental and genetic classification for malformations of cortical development: update 2012. *Brain* **135**, 1348-1369.

9. Edwards AD, Tan S (2006) Perinatal infections, prematurity and brain injury. *Current opinion in pediatrics* **18**, 119-124.

10. Volpe JJ (2009) Brain injury in premature infants: a complex amalgam of destructive and developmental disturbances. *Lancet Neurol* **8**, 110-124.

11. Oskoui M, Gazzellone MJ, Thiruvahindrapuram B *et al.* (2015) Clinically relevant copy number variations detected in cerebral palsy. *Nature communications* **6**, 7949.

12. Surveillance of Cerebral Palsy in E (2000) Surveillance of cerebral palsy in Europe: a collaboration of cerebral palsy surveys and registers. Surveillance of Cerebral Palsy in Europe (SCPE). *Dev Med Child Neurol* **42**, 816-824.

13. Palisano R, Rosenbaum P, Walter S *et al.* (1997) Development and reliability of a system to classify gross motor function in children with cerebral palsy. *Dev Med Child Neurol* **39**, 214-223.

14. Palisano RJ, Rosenbaum P, Bartlett D *et al.* (2008) Content validity of the expanded and revised Gross Motor Function Classification System. *Dev Med Child Neurol* **50**, 744-750.

15. Eliasson AC, Krumlinde-Sundholm L, Rosblad B *et al.* (2006) The Manual Ability Classification System (MACS) for children with cerebral palsy: scale development and evidence of validity and reliability. *Dev Med Child Neurol* **48**, 549-554.

16. Hidecker MJ, Paneth N, Rosenbaum PL *et al.* (2011) Developing and validating the Communication Function Classification System for individuals with cerebral palsy. *Dev Med Child Neurol* **53**, 704-710.

17. Rosenbaum P, Eliasson AC, Hidecker MJ *et al.* (2014) Classification in childhood disability: focusing on function in the 21st century. *J Child Neurol* **29**, 1036-1045.

18. Himmelmann K, Beckung E, Hagberg G *et al.* (2006) Gross and fine motor function and accompanying impairments in cerebral palsy. *Dev Med Child Neurol* **48**, 417-423.

19. Shumway-Cook A, Woollacott MH (2012) *Motor control : translating research into clinical practice*. 4th ed. Philadelphia: Wolters Kluwer Health/Lippincott Williams & Wilkins.

20. Shumway-Cook A, Woollacott MH (2012) Normal postural control. In *Motor control : translating research into clinical practice*, 4th ed., pp. 161-194. Philadelphia: Wolters Kluwer Health/Lippincott Williams & Wilkins.

21. Horak F, MacPherson J (1996) Postural orientation and equilibrium. In *Handbook of physiology*, pp. 255-292. New York: Published for the American Physiological Society by Oxford University Press.

22. Berthoz A (2000) The sense of movement: A sixth sense? In *The brain's sense of movement*, pp. 25-56. Cambridge, Mass.: Harvard University Press.

23. Berthoz A, Zaoui M (2015) New paradigms and tests for evaluating and remediating visuospatial deficits in children. *Dev Med Child Neurol* **57 Suppl 2**, 15-20.

24. Berthoz A (2000) Frames of reference. In *The brain's sense of movement*, pp. 97-114 [S Kosslyn, editor]. Cambridge, Mass.: Harvard University Press.

25. Fitzpatrick D (2008) The Somatic Sensory System: Touch and Proprioception. In *Neuroscience*, 4th ed., pp. 207-229 [DA Purves, George, J. Fitzpatrick, David. Hall, William, C. LaMantia, Anthony-Samuel. McNamara, James, O. White, Leonard; E, editor]. Sunderland, Mass.: Sinauer.

26. Maisson J, Woollacott M (2004) Posture and Equilibrium. In *Clinical disorders of balance, posture and gait*, 2nd ed., pp. viii, 466 p. [A Bronstein, T Brandt and M Woollacott, editors]. London, New York, NY: Arnold; Distributed in the U.S. of America by Oxford University Press.

27. Berthoz A (2000) Perception is simulated action. In *The brain's sense of movement*, pp. 9-24. Cambridge, Mass.: Harvard University Press.

28. Woollacott M, Shumway-Cook A (2002) Attention and the control of posture and gait: a review of an emerging area of research. *Gait Posture* **16**, 1-14.

29. Damiano DL, Wingert JR, Stanley CJ *et al.* (2013) Contribution of hip joint proprioception to static and dynamic balance in cerebral palsy: a case control study. *Journal of neuroengineering and rehabilitation* **10**, 57.

30. Rose J, Wolff DR, Jones VK *et al.* (2002) Postural balance in children with cerebral palsy. *Dev Med Child Neurol* **44**, 58-63.

31. Donker SF, Ledebt A, Roerdink M *et al.* (2008) Children with cerebral palsy exhibit greater and more regular postural sway than typically developing children. *Exp Brain Res* **184**, 363-370.

32. Saxena S, Rao BK, Kumaran S (2014) Analysis of postural stability in children with cerebral palsy and children with typical development: an observational study. *Pediatr Phys Ther* **26**, 325-330.

33. Burtner PA, Woollacott MH, Craft GL *et al.* (2007) The capacity to adapt to changing balance threats: a comparison of children with cerebral palsy and typically developing children. *Dev Neurorehabil* **10**, 249-260.

34. Chen J, Woollacott MH (2007) Lower extremity kinetics for balance control in children with cerebral palsy. *J Mot Behav* **39**, 306-316.

35. Girolami GL, Shiratori T, Aruin AS (2011) Anticipatory postural adjustments in children with hemiplegia and diplegia. *J Electromyogr Kinesiol* **21**, 988-997.

36. Liu WY, Zaino CA, McCoy SW (2007) Anticipatory postural adjustments in children with cerebral palsy and children with typical development. *Pediatr Phys Ther* **19**, 188-195.

37. Tomita H, Fukaya Y, Ueda T *et al.* (2011) Deficits in task-specific modulation of anticipatory postural adjustments in individuals with spastic diplegic cerebral palsy. *Journal of neurophysiology* **105**, 2157-2168.

38. Ferrari A, Tersi L, Sghedoni A *et al.* (2010) Functional reaching discloses perceptive impairment in diplegic children with cerebral palsy. *Gait Posture* **32**, 253-258.

39. Cherng RJ, Su FC, Chen JJ *et al.* (1999) Performance of static standing balance in children with spastic diplegic cerebral palsy under altered sensory environments. *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists* **78**, 336-343.

40. Lin JP (2003) The cerebral palsies: a physiological approach. *J Neurol Neurosurg Psychiatry* **74 Suppl 1**, i23-29.

41. Russell D, Rosenbaum P, Wright M *et al.* (2013) *Gross motor function measure (GMFM-66 & GMFM-88) user's manual*, *Clinics in developmental medicine* Devon, UK: Mac Keith Press.

42. Russell DJ, Rosenbaum PL, Cadman DT *et al.* (1989) The gross motor function measure: a means to evaluate the effects of physical therapy. *Dev Med Child Neurol* **31**, 341-352.

43. Russell DJ, Avery LM, Rosenbaum PL *et al.* (2000) Improved scaling of the gross motor function measure for children with cerebral palsy: evidence of reliability and validity. *Phys Ther* **80**, 873-885.

44. Begnoche DM, Chiarello LA, Palisano RJ *et al.* (2016) Predictors of Independent Walking in Young Children With Cerebral Palsy. *Phys Ther* **96**, 183-192.

45. Rosenbaum PL, Walter SD, Hanna SE *et al.* (2002) Prognosis for gross motor function in cerebral palsy: creation of motor development curves. *Jama* **288**, 1357-1363.

46. Tieman BL, Palisano RJ, Gracely EJ *et al.* (2004) Gross motor capability and performance of mobility in children with cerebral palsy: a comparison across home, school, and outdoors/community settings. *Phys Ther* **84**, 419-429.

47. Tieman B, Palisano RJ, Gracely EJ *et al.* (2007) Variability in mobility of children with cerebral palsy. *Pediatr Phys Ther* **19**, 180-187.

48. Lance JW (1980) Pathophysiology of spasticity and clinical experience with baclofen. In *Spasticity : disordered motor control*, pp. 185-220 [R Feldman, R Young and W Koella, editors]. Chicago, IL: Year Book Medical Publishers.

49. Bohannon RW, Smith MB (1987) Interrater reliability of a modified Ashworth scale of muscle spasticity. *Phys Ther* **67**, 206-207.

50. Hagglund G, Wagner P (2008) Development of spasticity with age in a total population of children with cerebral palsy. *BMC Musculoskelet Disord* **9**, 150.

51. Ross SA, Engsberg JR (2007) Relationships between spasticity, strength, gait, and the GMFM-66 in persons with spastic diplegia cerebral palsy. *Arch Phys Med Rehabil* **88**, 1114-1120.

52. Gorter JW, Verschuren O, van Riel L *et al.* (2009) The relationship between spasticity in young children (18 months of age) with cerebral palsy and their gross motor function development. *BMC Musculoskelet Disord* **10**, 108.

53. Chiarello LA, Palisano RJ, Bartlett DJ *et al.* (2011) A multivariate model of determinants of change in gross-motor abilities and engagement in self-care and play of young children with cerebral palsy. *Phys Occup Ther Pediatr* **31**, 150-168.

54. Bartlett DJ, Palisano RJ (2002) Physical therapists' perceptions of factors influencing the acquisition of motor abilities of children with cerebral palsy: implications for clinical reasoning. *Phys Ther* **82**, 237-248.

55. Sanger TD, Chen D, Delgado MR *et al.* (2006) Definition and classification of negative motor signs in childhood. *Pediatrics* **118**, 2159-2167.

56. Damiano DL, Dodd K, Taylor NF (2002) Should we be testing and training muscle strength in cerebral palsy? *Dev Med Child Neurol* **44**, 68-72.

57. Wiley ME, Damiano DL (1998) Lower-extremity strength profiles in spastic cerebral palsy. *Dev Med Child Neurol* **40**, 100-107.

58. Eek MN, Beckung E (2008) Walking ability is related to muscle strength in children with cerebral palsy. *Gait Posture* **28**, 366-371.

59. Scholtes VA, Becher JG, Comuth A *et al.* (2010) Effectiveness of functional progressive resistance exercise strength training on muscle strength and mobility in children with cerebral palsy: a randomized controlled trial. *Dev Med Child Neurol* **52**, e107-113.

60. Bania TA, Dodd KJ, Baker RJ *et al.* (2016) The effects of progressive resistance training on daily physical activity in young people with cerebral palsy: a randomised controlled trial. *Disabil Rehabil* **38**, 620-626.

61. Boyd RN (2012) Functional progressive resistance training improves muscle strength but not walking ability in children with cerebral palsy. *J Physiother* **58**, 197.

62. Steele KM, Damiano DL, Eek MN *et al.* (2012) Characteristics associated with improved knee extension after strength training for individuals with cerebral palsy and crouch gait. *J Pediatr Rehabil Med* **5**, 99-106.

63. Ostensjo S, Carlberg EB, Vollestad NK (2004) Motor impairments in young children with cerebral palsy: relationship to gross motor function and everyday activities. *Dev Med Child Neurol* **46**, 580-589.

64. Vos RC, Becher JG, Voorman JM *et al.* (2016) Longitudinal association between gross motor capacity and neuromusculoskeletal function in children and youth with cerebral palsy. *Arch Phys Med Rehabil*.

65. Asaka T, Wang Y, Fukushima J *et al.* (2008) Learning effects on muscle modes and multi-mode postural synergies. *Exp Brain Res* **184**, 323-338.

66. Busse ME, Wiles CM, van Deursen RWM (2005) Muscle coactivation in neurological conditions. *Physical Therapy Reviews* **10**, 247-253.

67. Tedroff K, Knutson LM, Soderberg GL (2008) Co-activity during maximum voluntary contraction: a study of four lower-extremity muscles in children with and without cerebral palsy. *Dev Med Child Neurol* **50**.

68. Eken MM, Dallmeijer AJ, Doorenbosch CA *et al.* (2016) Coactivation During Dynamometry Testing in Adolescents With Spastic Cerebral Palsy. *Phys Ther*.

69. Nordmark E, Hagglund G, Lauge-Pedersen H *et al.* (2009) Development of lower limb range of motion from early childhood to adolescence in cerebral palsy: a population-based study. *BMC medicine* **7**, 65.

70. Tedroff K, Granath F, Forssberg H *et al.* (2009) Long-term effects of botulinum toxin A in children with cerebral palsy. *Dev Med Child Neurol* **51**, 120-127.

71. Rodby-Bousquet E, Czuba T, Hagglund G *et al.* (2013) Postural asymmetries in young adults with cerebral palsy. *Dev Med Child Neurol* **55**, 1009-1015.

72. Westcott SL, Lowes LP, Richardson PK (1997) Evaluation of postural stability in children: current theories and assessment tools. *Phys Ther* **77**, 629-645.

73. Lowes LP, Westcott SL, Palisano RJ *et al.* (2004) Muscle force and range of motion as predictors of standing balance in children with cerebral palsy. *Phys Occup Ther Pediatr* **24**, 57-77.

74. Jacobson LK, Dutton GN (2000) Periventricular leukomalacia: an important cause of visual and ocular motility dysfunction in children. *Survey of ophthalmology* **45**, 1-13.

75. Ego A, Lidzba K, Brovedani P *et al.* (2015) Visual-perceptual impairment in children with cerebral palsy: a systematic review. *Dev Med Child Neurol* **57 Suppl 2**, 46-51.

76. Fazzi E, Signorini SG, La Piana R *et al.* (2012) Neuro-ophthalmological disorders in cerebral palsy: ophthalmological, oculomotor, and visual aspects. *Dev Med Child Neurol* **54**, 730-736.

77. McLaughlin JF, Felix SD, Nowbar S *et al.* (2005) Lower extremity sensory function in children with cerebral palsy. *Pediatric rehabilitation* **8**, 45-52.

78. Wingert JR, Burton H, Sinclair RJ *et al.* (2009) Joint-position sense and kinesthesia in cerebral palsy. *Arch Phys Med Rehabil* **90**, 447-453.

79. Petrarca M, Cappa P, Zanelli G *et al.* (2013) Spatial rotational orientation ability in standing children with cerebral palsy. *Gait Posture* **37**, 494-499.

80. Schmit J, Riley M, Cummins-Sebree S *et al.* (2015) Children with cerebral palsy effectively modulate postural control to perform a supra-postural task. *Gait Posture* **42**, 49-53.

81. Tedroff K, Lowing K, Jacobson DN *et al.* (2011) Does loss of spasticity matter? A 10-year follow-up after selective dorsal rhizotomy in cerebral palsy. *Dev Med Child Neurol* **53**, 724-729.

82. Morton RE, Gray N, Vloeberghs M (2011) Controlled study of the effects of continuous intrathecal baclofen infusion in non-ambulant children with cerebral palsy. *Dev Med Child Neurol* **53**, 736-741.

83. Molenaers G, Van Campenhout A, Fagard K *et al.* (2010) The use of botulinum toxin A in children with cerebral palsy, with a focus on the lower limb. *J Child Orthop* **4**, 183-195.

84. Novak I, McIntyre S, Morgan C *et al.* (2013) A systematic review of interventions for children with cerebral palsy: state of the evidence. *Dev Med Child Neurol* **55**, 885-910.

85. Hasnat MJ, Rice JE (2015) Intrathecal baclofen for treating spasticity in children with cerebral palsy. *Cochrane Database Syst Rev* **11**, Cd004552.

86. Tedroff K, Lowing K, Astrom E (2015) A prospective cohort study investigating gross motor function, pain, and health-related quality of life 17 years after selective dorsal rhizotomy in cerebral palsy. *Dev Med Child Neurol* **57**, 484-490.

87. Dallmeijer AJ, Rameckers EA, Houdijk H *et al.* (2015) Isometric muscle strength and mobility capacity in children with cerebral palsy. *Disabil Rehabil*, 1-8.

88. Thompson N, Stebbins J, Seniorou M *et al.* (2011) Muscle strength and walking ability in diplegic cerebral palsy: implications for assessment and management. *Gait Posture* **33**, 321-325.

89. Damiano DL, Abel MF (1998) Functional outcomes of strength training in spastic cerebral palsy. *Arch Phys Med Rehabil* **79**, 119-125.

90. Brogren E, Hadders-Algra M, Forssberg H (1998) Postural control in sitting children with cerebral palsy. *Neurosci Biobehav Rev* **22**, 591-596.

91. Brogren E, Forssberg H, Hadders-Algra M (2001) Influence of two different sitting positions on postural adjustments in children with spastic diplegia. *Dev Med Child Neurol* **43**, 534-546.

92. Burtner PA, Qualls C, Woollacott MH (1998) Muscle activation characteristics of stance balance control in children with spastic cerebral palsy. *Gait Posture* **8**, 163-174.

93. Ferrari A, Sghedoni A, Alboresi S *et al.* (2014) New definitions of 6 clinical signs of perceptual disorder in children with cerebral palsy: an observational study through reliability measures. *Eur J Phys Rehabil Med* **50**, 709-716.

94. Bartonek A, Lidbeck CM, Gutierrez-Farewik EM (2016) Influence of External Visual Focus on Gait in Children With Bilateral Cerebral Palsy. *Pediatr Phys Ther*.

95. Alboresi A, Belmonti V, Ferrari A *et al.* (2010) Dysperceptive forms. In *The spastic forms of cerebral palsy : a guide to the assessment of adaptive functions*, pp. 273-290 [A Ferrari and G Cioni, editors]. Milano: Springer.

96. Mutlu A, Livanelioglu A, Gunel MK (2008) Reliability of Ashworth and Modified Ashworth scales in children with spastic cerebral palsy. *BMC Musculoskelet Disord* **9**, 44.

97. Joint motion: method of measuring and recording. In *American Academy of Orthopaedic Surgeons* Edinburgh, London, Melbourne: Churchill Livingstone. 1988.

98. Mutlu A, Livanelioglu A, Gunel MK (2007) Reliability of goniometric measurements in children with spastic cerebral palsy. *Med Sci Monit* **13**, Cr323-329.

99. Ramakrishnan HK, Kadaba MP (1991) On the estimation of joint kinematics during gait. *J Biomech* **24**, 969-977.

100. Hermens HJ, Freriks B, Disselhorst-Klug C *et al.* (2000) Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol* **10**, 361-374.

101. Willemse L, Brehm MA, Scholtes VA *et al.* (2013) Reliability of isometric lower-extremity muscle strength measurements in children with cerebral palsy: implications for measurement design. *Phys Ther* **93**, 935-941.

102. Verschuren O, Ketelaar M, Takken T *et al.* (2008) Reliability of hand-held dynamometry and functional strength tests for the lower extremity in children with Cerebral Palsy. *Disabil Rehabil* **30**, 1358-1366.

103. Crompton J, Galea MP, Phillips B (2007) Hand-held dynamometry for muscle strength measurement in children with cerebral palsy. *Dev Med Child Neurol* **49**, 106-111.

104. Eek MN, Kroksmark AK, Beckung E (2006) Isometric muscle torque in children 5 to 15 years of age: normative data. *Arch Phys Med Rehabil* **87**, 1091-1099.

105. Podsiadlo D, Richardson S (1991) The timed "Up & Go": a test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society* **39**, 142-148.

106. Williams EN, Carroll SG, Reddihough DS *et al.* (2005) Investigation of the timed 'up & go' test in children. *Dev Med Child Neurol* **47**, 518-524.

107. Hyvarinen L, Nasanen R, Laurinen P (1980) New visual acuity test for pre-school children. *Acta Ophthalmol (Copenh)* **58**, 507-511.

108. Moutakis K, Stigmar G, Hall-Lindberg J (2004) Using the KM visual acuity chart for more reliable evaluation of amblyopia compared to the HVOT method. *Acta ophthalmologica Scandinavica* **82**, 547-551.

109. Sample PA, Dannheim F, Artes PH *et al.* (2011) Imaging and Perimetry Society standards and guidelines. *Optometry and vision science : official publication of the American Academy of Optometry* **88**, 4-7.

110. Sheridan MD (1973) The STYCAR graded-balls vision test. *Dev Med Child Neurol* **15**, 423-432.

111. Dallmeijer AJ, Baker R, Dodd KJ *et al.* (2011) Association between isometric muscle strength and gait joint kinetics in adolescents and young adults with cerebral palsy. *Gait Posture* **33**, 326-332.

112. Saavedra S, Woollacott M, van Donkelaar P (2010) Head stability during quiet sitting in children with cerebral palsy: effect of vision and trunk support. *Exp Brain Res* **201**, 13-23.

113. Wood E, Rosenbaum P (2000) The gross motor function classification system for cerebral palsy: a study of reliability and stability over time. *Dev Med Child Neurol* **42**, 292-296.

114. Örtqvist M, Bartonek Å, Gutierrez-Farewik EM *et al.* (2014) Knee muscle strength - A challenge to measure. *European Journal of Physiotherapy* **16**, 33-40.

115. Tedroff K, Knutson LM, Soderberg GL (2006) Synergistic muscle activation during maximum voluntary contractions in children with and without spastic cerebral palsy. *Dev Med Child Neurol* **48**, 789-796.